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User's Manual for Premining Planning of Eastern Surface Coal Mining - Volume 5: Mine Drainage Management and Monitoring

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This volume is the fifth in a series of six reports designed to provide the surface coal mining industry and its regulators with a comprehensive review of the best available methods for extracting coal while protecting the environment. The six-volume report examines the surface mining of coal in the Eastern United States and sets guidelines for developing, evaluating, and selecting mining and reclamation plans that will be the least detrimental to the environment.

This report is concerned with mine drainage management and monitoring. The objective of the report is to provide a technical background on which to establish pragmatic guidelines for making decisions regarding water quality management in surface mining. This report is divided into four major areas of concentration. The first area provides a general overview of the problem of mine drainage control and the nature of mine drainage water. The second area presents a review of techniques commonly used for drainage abatement and water quality control in surface mining. The third area examines a number of experimental techniques currently being considered as having some potential for controlling mine drainage water. The fourth area reviews the various aspects of the monitoring programs.

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Mine Drainage Management and Monitoring

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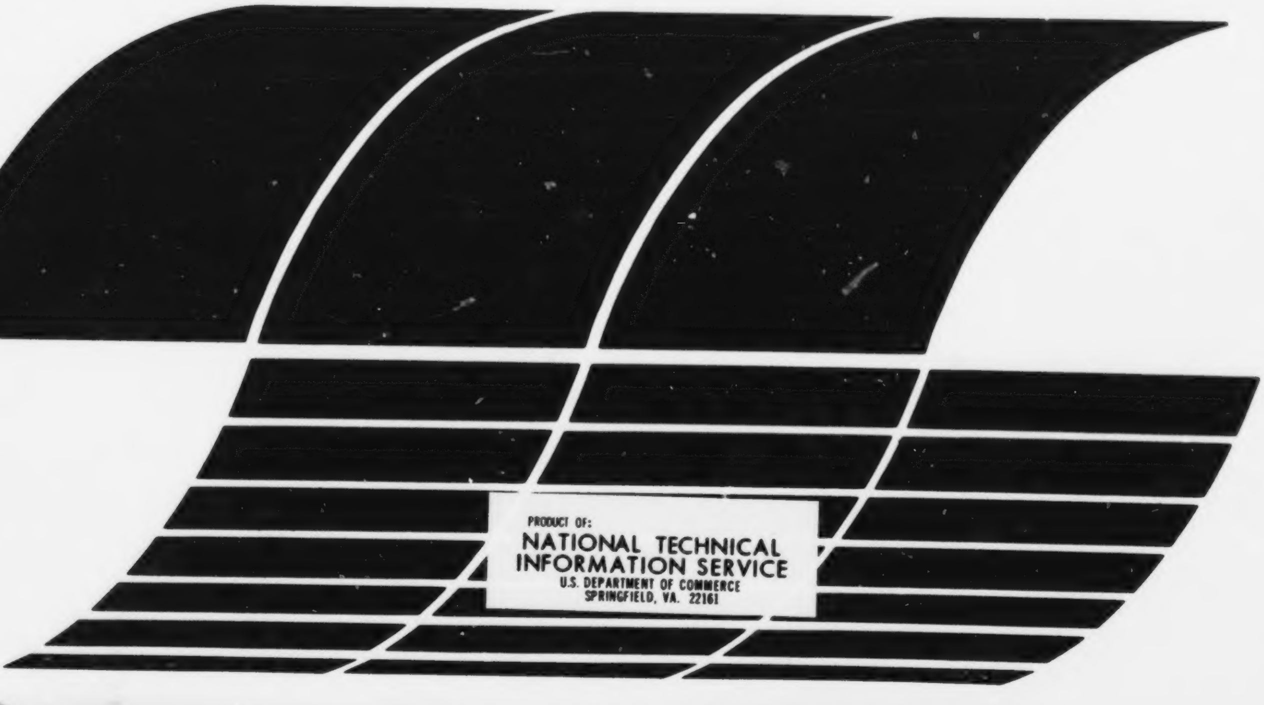

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USER'S MANUAL FOR PREMINING PLANNING OF EASTERN SURFACE COAL MINING
Volume 5: Mine Drainage Management and Monitoring

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FOREWORD

When energy and material resources are extracted, processed, converted, and used, the related pollutional impacts on our environment and even on our health often require that new and increasingly more efficient pollution control methods be used. The Industrial Environmental Research Laboratory-Cincinnati (IERL-Ci) assists in developing and demonstrating new and improved methodologies that will meet these needs both efficiently and economically.

This volume is the fifth in a series of six reports designed to provide the surface coal mining industry and its regulators with a comprehensive review of the best available methods for extracting this valuable mineral resource while protecting the fragile environment. This report aims to provide a technical background on which to establish pragmatic guidelines for directing decisions regarding water quality management in surface mining.

David G. Stephan
Director
Industrial Environmental Research Laboratory
Cincinnati

ABSTRACT

This volume is the fifth in a series of six reports designed to provide the surface coal mining industry and its regulators with a comprehensive review of the best available methods for extracting coal while protecting the fragile environment. Recommendations for selecting and designing mining systems were based on a review and critical evaluation of the methods reported in the literature and applied in the field. The six-volume report examines the surface mining of coal in the Eastern United States and sets guidelines for developing, evaluating, and selecting mining and reclamation plans that will be the least detrimental to the environment. The scope of the study was to consider the geological and hydrological settings before mining as basic inputs to premining planning, and to develop guidelines for assessing alternatives in the areas of surface mine engineering, water management, and mine land planning.

Volume 5 is concerned with mine drainage management and monitoring. The objective of the report is to provide a technical background on which to establish pragmatic guidelines for making decisions regarding water quality management in surface mining. This report is divided into four major areas of concentration. The first area provides a general overview of the problem of mine drainage control and the nature of mine drainage water. The second area presents a review of techniques commonly used for drainage abatement and water quality control in surface mining. The third area examines a number of experimental techniques currently being considered as having some potential for controlling mine drainage water. The fourth area reviews the various aspects of the monitoring programs.

This report was submitted in fulfillment of Grant No. R803882 by the Department of Mineral Engineering and the Department of Geosciences of The Pennsylvania State University under the sponsorship of the U.S. Environmental Protection Agency. The report covers the period July 1, 1975, to May 30, 1978, and work was completed as of June 1, 1978.

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ABBREVIATIONS

APHA -- American Public Health Association
ASTM -- American Society for Testing and Materials
atm -- atmosphere
cfs -- cubic feet per second
cm -- centimeter
Eh -- oxidation potential
EPA -- U.S. Environmental Protection Agency
FHA -- Federal Highway Administration
ft -- foot
h -- hour
in -- inch
kg -- kilogram
km -- kilometer
ℓ -- liter
ℓ/sec -- liters per second
m -- meter
NCA -- National Coal Association
NWC -- National Water Commission
Pa -- Pennsylvania
PennDOT -- Pennsylvania Department of Transportation
PSU -- The Pennsylvania State University
s -- second
USBM -- U.S. Bureau of Mines

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The materials presented here represent a joint effort by the Department of Mineral Engineering and the Department of Geosciences of the College of Earth and Mineral Sciences, The Pennsylvania State University. The work performed in the preparation of this report was under the direction of Dr. H. Lovell of the Mineral Engineering Department, who provided the overall structure of the report. He was assisted by Mr. D. Forsberg, Ms. D. Richardson, and Ms. A. Weiner, graduate assistants in Mineral Engineering. The efforts of the Geosciences group were directed by Dr. R. R. Parizek, who was assisted by Ms. J. Herman, research assistant in Geosciences. Mr. M. Clar, research assistant in Mining Engineering, acted as project coordinator and assisted in integrating the efforts of the two groups and editing of the final report.

Financial support for the completion aspects of the work performed by the Geosciences group was provided by the Mineral Conservation Section, The Pennsylvania State University. Principal funding was provided by EPA Grant No. R803882.

PROJECT STAFF

The materials contained in the manual were prepared by an interdepartmental and interdisciplinary group of the College of Earth and Mineral Sciences of The Pennsylvania State University. Overall management for the project was provided by the Department of Mineral Engineering. The project staff was comprised of the following personnel:

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SECTION 1

INTRODUCTION

Volume 5 is part of a six-volume series of reports designed to provide the surface coal mining industry and its regulators with a comprehensive review of the best available and least environmentally detrimental methods for extracting coal. This volume is concerned with the water quality management aspects of surface coal mining practice in the Eastern United States. The specific study region is defined in Volume I, the executive summary. The objective of this report is to provide a technical background on which to establish pragmatic guidelines for making decisions regarding water quality management in surface mining. Related aspects concerned with water volume are considered separately in Volume 4, Mine Hydrology. Because it is very difficult to separate the qualitative and quantitative aspects of water resources management, some degree of overlapping exists between Volumes 4 and 5 of this manual. Consequently, the user is advised to refer to these two volumes jointly.

The estimated amount of coal recoverable in the United States by surface mining* has increased through the years (U.S. Bureau of Mines, 1971), primarily because of the availability of larger equipment (Haley, 1974). However, the potential advantages of economic coal recovery using larger stripping ratios are accompanied by additional economic and technical considerations, especially environmental problems. Firmer mining regulations regarding water effluents for point sources (Coal Mining Operating Regulations, 1976) and recently developed nonpoint source philosophy (U.S. Environmental Protection Agency, 1976) have better defined these problems. Water quality aspects of surface mining frequently become complex and challenging, creating problems that potentially supersede those of direct control of the overburden and surface reclamation.

The extent of permissible water degradation occasioned by surface mining is defined by law (Coal Mining Operating Regulations, 1976; Coal Mining Effluent Guidelines and Standards, 1977; and U.S. Environmental Protection Agency, 1976). Though the goal may be to cause no change in water quality as a result of surface mining, temporary and minimal water quality degradation may be unavoidable if these critical energy resources are to be exploited for current societal demands. The achievement of the control technically possible, like most environmental problems, results in increased direct costs; but if water degradation were to continue unchecked, indirect reclamation costs could be even greater. Accordingly, optimal economic water quality control must be attained, or the cost of deriving energy from coal will work to the disadvantage of the individual and the nation. This report reviews man's technological capability and the economic implications of managing water quality during surface mining using procedures that coordinate pollution control with the engineering aspects of coal mining.

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*The 1974 reserve base was 173 billion tons (Averitt, 1975; Dupree, et al., 1976), but it represented less than 30 percent of the total coal reserves when expressed on a calorific basis.

This volume is divided into four main areas: (1) an overview of the mine drainage control problem, (2) common techniques used for drainage abatement and water quality control, (3) experimental drainage abatement techniques, and (4) monitoring. A few of the basic considerations that must be part of any mine drainage control program are discussed briefly in this section.

CONTACT OF WATERS WITH DISTURBED MINERAL SURFACES

The modification (usually quality degradation) of prevailing water quality by surface mining results from the dispersion, reaction, and solution of mineral components by the water as a consequence of the disruption of surface and near-surface strata equilibria by the mining process. Prevention of water quality degradation must be based on measures to avoid or minimize contact of the waters with the disturbed mineral surfaces. Only trace levels of grease, oils, debris, or explosive residuals are, unavoidably, added to the waters directly from the mechanical operations.

LENGTH OF TREATMENT

Situations exist where adequate water quality control can be achieved only by continuous water treatment before release to surface streams. These actions may be necessary over long periods of time and should be avoided and/or minimized, if possible.

COST CONSIDERATIONS

The water quality control cost levels are generally higher in the Eastern United States for several reasons. Seams are thinner, and the ratio of acreage disturbed to coal recovered is greater. There is a tendency to have overburden that is more highly acidic in the East, a condition that enhances the degradation of water quality. In addition, the more abundant precipitation accelerates acid reactions, and the population density of this area justifies the protection of water sources from physical and chemical damage.

Traditional surface mine operations have tended to ignore control of water quality or viewed it as an expensive nuisance. The cost of providing for adequate treatment of mine waters should be considered in the initial mining feasibility study. Special techniques may be necessary in certain instances (such as compaction of overburden and placement of rock barriers for erosion control, Figures 1 and 2) that greatly increase project costs.

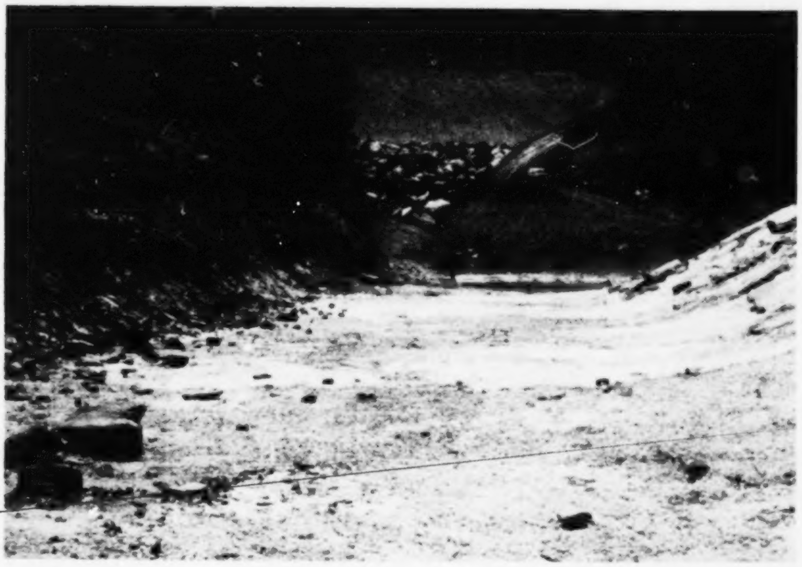

Figure 1. Rock boulders at toe of valley fill area grading to sedimentation basin. Concrete spillway from basin provides for high water levels.

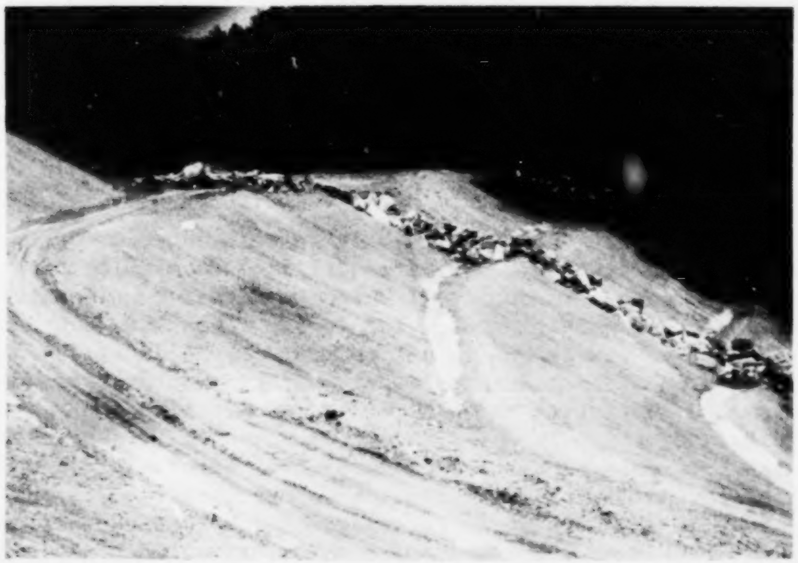

Figure 2. Valley fill showing water discharge rock core.

Premining plans must go beyond the requirements of the permit applications to coordinate the control of potential water pollution with the development of mining systems. Inadequate premining environmental planning and failure to take appropriate actions during mining can lead to intolerable treatment costs, environmental degradation, long-term treatment requirements, and even legal actions.

SITE CHARACTERISTICS

Topography

The surface mining practices in the study area have been classified (Skelly and Loy, 1975) into three groups based on regional topography: (1) Steep slopes with contour mining along the outcrop. These locations may be least vulnerable to water quality changes, but most susceptible to siltation problems (Hittman Associates, 1976). (2) Rolling terrain with modified area and multiple-cut contour mining. Since these operations occur below hill crowns and interrupt aquifer-groundwater tables, they can be conducive to larger water flows and quality changes. (3) Flat terrain with thick overburden and box-cut area mining. The depth of these cuts commonly disrupts large, more regional aquifers, implicating large volumes of slow-moving groundwaters. The mineralogy and geochemistry of the strata (pyrite vs. alkaline minerals) subsequently become critical factors in water quality changes. The potential for water quality change is great.

Geology

Consideration must be given to the local geology (Caruccio and Ferris, 1974; see also Volume 4 of this report, Mine Hydrology), including stratigraphy, mineralogy, groundwater pollution potential, and flow levels. Detailed mapping should be conducted to establish topography, subsurface and surface water flows, and lineament-fracture traces and other water-controlling structures. Plans must be established in advance for surface water control, water pollution prevention and treatment techniques, and backfilling and surface reclamation procedures.

Site exploration relies heavily on coal outcrop observations and documented regional geology. Specific drilling data collection procedures vary from scattered and random drill holes to detailed grid patterns. Unfortunately, the acquisition of water level, flow rate, and quality data during these drilling operations is not common; nor is detailed evaluation of cores for strata identification and water pollution potential. Core samples should be examined for pyrite and alkalinity characterization, as well as for other measures indicative of water pollution potential. These core samples often are the only data source for planning coal beneficiation operations, including estimation of quantities and characteristics of refuse reject. These data provide a useful guide for water quality management. Geophysical logging techniques such as gamma-gamma density logs, natural gamma ray logs, neutron logs, and resistivity have only recently been introduced into coal site exploration and offer potentially powerful contributions. Exploration samples should be subject to topsoil evaluation, which is critical in reclamation and revegetation. These concerns extend to edaphology and the nature of the soils and their fertility. Such data become helpful in the planning of topsoil replacement following its temporary storage. Current soil reference sources that should be consulted for details include Taylor and Ashcroft, 1972; Brady, 1974; Tisdale and Nelson, 1975; Jackson, 1970; and Black, 1965. Aerial remote sensing can be used to establish the locations of concentrated soils and groundwater flows, regions of increased permeability, and significant hydraulic head changes within structures revealed by lineaments and fracture traces (Lovell and Gunnet, 1974; see also Volume 3 of this report, Geology of Eastern Coalfields, and Volume 4, Mine Hydrology).

TRANSPORTATION, STORAGE AND COAL PREPARATION

Related coal mining activities such as transportation, storage of mineral products, and coal preparation can contribute to water pollution problems. A detailed discussion of these associated problems is beyond the scope of the report, but general considerations will be presented.

Transportation of surface-mined coals is not normally a major problem with respect to water quality. If special haul roads are constructed, these roads must be properly designed to collect surface runoff and release it without causing environmental degradation. Frequently, culverts carrying surface runoff in high-slope areas release their flow directly at lower elevations at high velocities (Figure 3). Such discharges should be released via check sumps at lower velocities to prevent erosion (Figure 4).

Pipeline transport of coal is not currently applied in the study region, but it may become important. Careful control of water quality is necessary in this process, as is the definition of the surface water or groundwater supply sources that can sustain these prolonged water demands and the disposal or use of this water at the point of discharge.

The storage of surface-mined coal poses special problems in water quality management, especially those related to surface runoff. The availability of water resources for the study region is discussed in Volume 3 of this series, Geology of Eastern Coalfields. Occasionally in surface mining, bin or silo storage is practised which offers the greatest protection against degradation of water by drainage from mined coal. Primary control procedures for stockpiled coal involve diversion of water from the stockpile and collection of surface runoff waters around the storage area and their direction to settling basins for sedimentation and chemical treatment, if necessary. Potential water infiltration to the subsurface under a coal storage pile should not be ignored, as such infiltration can serve as a diffuse source of pollution.

Effluents from coal preparation facilities and ancillary areas are strictly regulated by current effluent guidelines (Coal Mining Effluent Guidelines and Standards, 1977) limiting iron, manganese, and total suspended solid concentrations and the pH of the water. These requirements may necessitate the construction of treatment facilities or the design of a

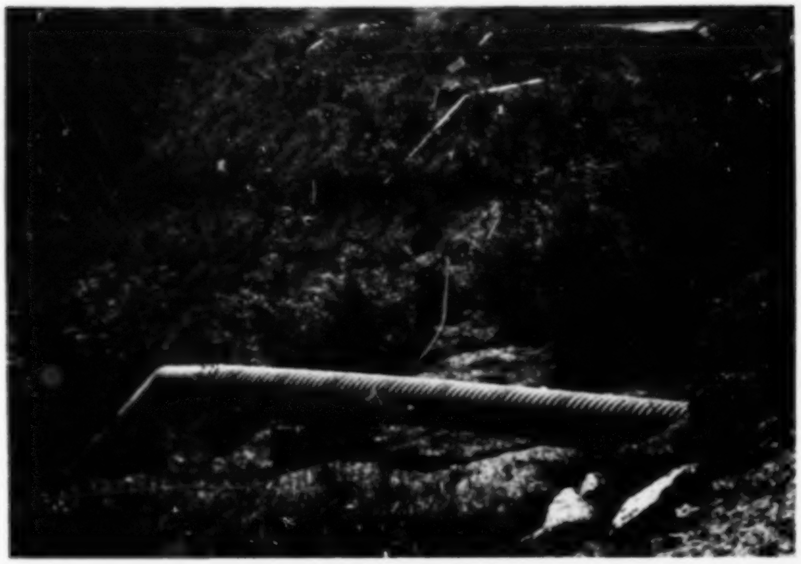

Figure 3. Haulroad culverts discharging surface waters at high velocities.

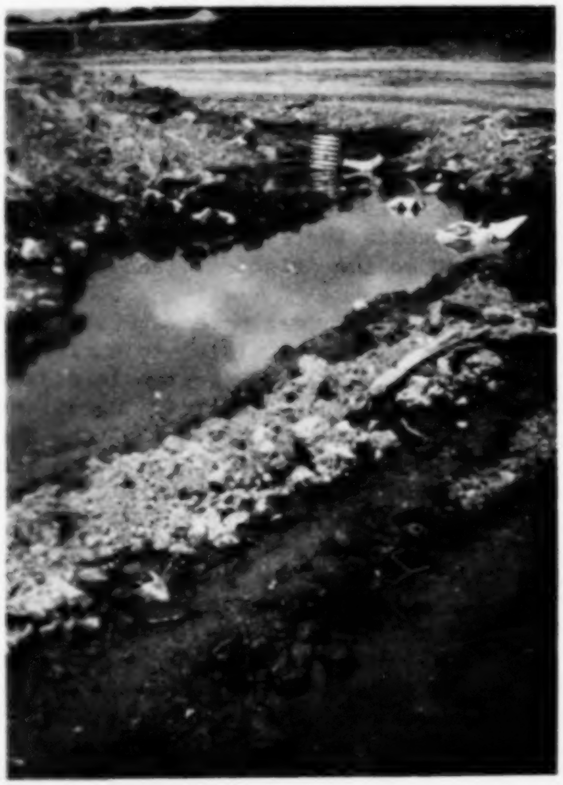

Figure 4. Diversion ditch sump along haulroad showing use of standpipe.

closed-circuit water system. Burial of coal refuse from the preparation plant with the overburden during backfilling should be accomplished in accordance with good water quality management practices to minimize the potential for water pollution (National Coal Association, 1974). The handling of preparation plant slime flows is sometimes coordinated with surface mine refuse disposal (Figure 5 and 6). Volume 4 stresses that the disposal of these wastes frequently results in a pollution problem from mines that lacked sources of alkalinity and that might otherwise have produced acceptable water quality. Care should be exercised when selecting mine disposal sites to exploit natural treatment processes where possible. The proximity of suitable refuse disposal sites should also be factored into the site location process for preparation plants.

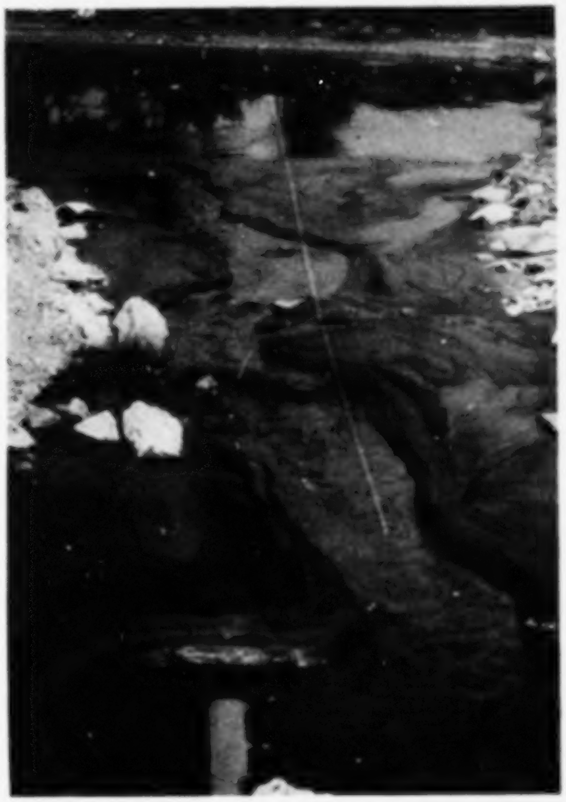

Figure 5. Coal preparation plant slimes being dewatered in surface mine operations.

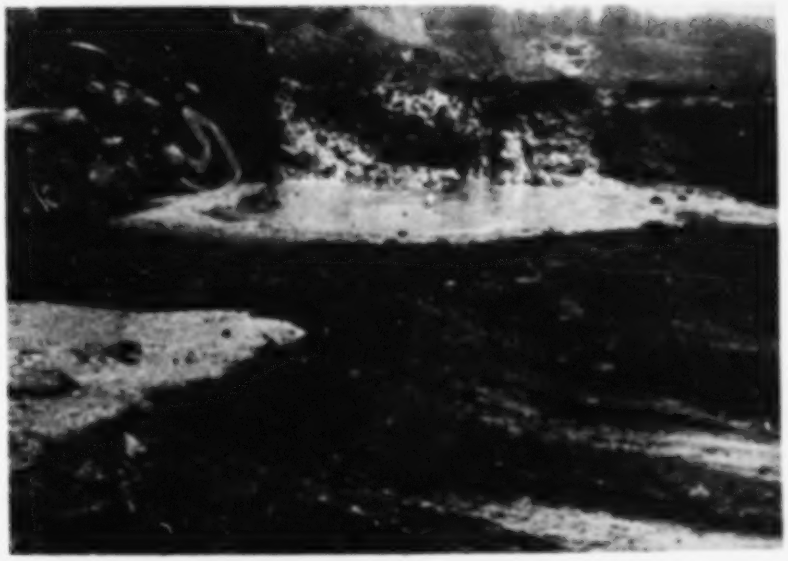

Figure 6. Coal preparation plant refuse slimes being built in surface mine.

SECTION 2

SUMMARY AND CONCLUSIONS

Since the quality of water discharged from surface mining is regulated, its control must become part of the planning process and is especially critical in the preparation of permit applications. Water quality control procedures should be coordinated with the development and application of the mining system and with final reclamation procedures. The technological approaches vary widely geographically, especially with the terrain and its near-surface characteristics.

Various mine restoration and mine drainage pollution abatement measures can be adopted to reduce or eliminate mine drainage originating within surface mines located in the eastern coal region watersheds. These should be selected with several factors considered. Mine drainage can be collected and treated during active mining. For selected mines, treatment may be required for a period in the future to eliminate pollutants that may persist following mine restoration. The hydrogeological and geochemical setting should be understood for the mining region where an abatement procedure is to be adopted to assess the magnitude of the problem expected during and following mining. Such knowledge will greatly increase the probability that the restoration program will have the intended benefits. Also, areas and methods should be selected for treatment where the maximum benefits can be achieved at the lowest cost. As pollution abatement measures become more complex, they will increase in cost. However, the long-term environmental costs to society may prove to be lower with the use of these initially more involved and costly abatement measures, since mine drainage pollution may continue long after mining and restoration are complete. Mine drainage runoff following mining may not be a point source of pollution, as was the case during mining; but it may appear as a more difficult to handle, diffuse source (i.e., scattered seepages and diffuse groundwater pollution).

STEPS IN PREMINING PLANNING

Planning for mine drainage control begins with accumulation of proper data during exploration, usually from drilling data, sample collection (strata and water), and aerial sensing. In addition to actual mining and area reclamation, attention must be given to coal, overburden, preparation plant, and transportation (especially haul roads); to the storage of mined coal; to coal preparation refuse disposal; and to economic relationships.

The phytogenic origin of coals over long periods of time has created a heterogeneity that requires specific engineering for each mining site. Accordingly, detailed coal and associated strata characteristics must be established.

The water encountered in surface mining originates from precipitation and is usually of the highest quality. The form and quantity of water reaching the earth's surface is distributed between surface runoff and that which moves underground near the surface. The ratio of the water distribution becomes a critical parameter and demands appropriate consideration of prevailing meteorological patterns. There is seldom significant change in quality of surface waters beyond their ability to cause erosion and carry sediment to the prevailing watershed drainage system. It is the control of flow rates that becomes critical.

In contrast, those waters that reach the subsurface serve as a continuing lixiviant, dissolving various levels of contacted strata or enhancing chemical reactions that result in the formation of water soluble substances. Accordingly, it is necessary to establish underground flow patterns and rates as well as the components of strata (not just coal seam components) that are potentially water soluble. The parameters of concern are the quality of the percolating waters, the solubility of individual minerals, and the rates of solution. The concern relates not only to man's mining activities that denude and disturb the near surface, but to the numerous natural phenomena that prevail in these complex systems.

Those mineralogical components of greatest interest that control the solution process include carbonates, sulfides (especially pyrite), and silicates (as regards alumina and silica release). There are numerous minor and trace substances (manganese, cadmium, zinc, etc.) that require special consideration.

Pyrite (FeS_2) is perhaps the most critical component. Despite its relative insolubility, it is capable of being oxidized (with air, water, and bacteria) to form highly water soluble sulfates that are especially deleterious to water quality. The parameters controlling pyrite oxidation include grain-size distribution/concentration, pyrite-water-oxygen contact potential, the crystalline nature of the pyrite, and various physical-chemical parameters such as water quality, the oxidation potential Eh, temperature, and flow rates. It has been shown that certain autotrophic bacteria also play an important role in pyrite oxidation.

Government regulations (State and Federal) have been developed, culminating in the Coal Mining Operating Regulations (1976), The Coal Mining Effluent Guidelines (1977), and the Surface Mining Control and Reclamation Act (1977).

APPROACHES TO WATER QUALITY CONTROL

The approaches to water quality control in surface mining involve the control of water movement, the nature of the overburden, the control of conditions with water pollution potential during active mining, the utilization of settling ponds, the treatment of waters, when necessary, to meet effluent standards, and the development of water storage areas as an alternative to direct release.

Control of Water Movement

The control of water movement may involve surface flow control and/or strata dewatering. The objective is to divert surface flows from the disturbed areas and to control those surface waters that reach the surface mine. Premining evaluation of these flows and of their quality is critical and should include establishment of regions of higher water permeability. Actual strata dewatering appears to offer a viable, low-cost alternative, but it has not been adequately demonstrated to date. Surface waters should be controlled and directed to settling basins for possible treatment and/or sediment removal.

Nature of the Overburden

The characteristics of the overburden should be established to determine the potential for water quality degradation from soluble components. Such data, usually obtained from core samples, result from chemical and mineralogical analyses of the strata and from analyses of water leached through the strata. Though standard tests for the latter analyses do not exist, they provide some useful guidelines. The leaching tests do not establish oxidation rate levels for pyrite. Overburden characterization does establish the presence of topsoil (for replacement) and potentially toxic strata that usually require segregation and selective replacement. The relative amounts of these overburden classes will establish handling and disposal procedures and some general mining costs.

Replacement of potentially toxic spoil requires the selection of locations that will either provide the least possible water contact (to minimize sulfide oxidation and water mineralization) or the greatest neutralization (because of the presence of alkaline soil and groundwater).

Control of Potentially Polluting Conditions

Mining procedures should minimize the amount of silt and coal fines introduced into waters encountered in the open pit. These effects minimize silt removal and water treatment requirements.

Utilization of Settling Ponds

Any waters that develop in the open cut should be pumped out promptly and transported (by pipe or ditch) to the settling basins. Flocculant use may be necessary to enhance silt and sludge settling rates. Flocculants require detailed attention for most effective use.

Water Treatment to Meet Effluent Standards

Water quality degradation may be minimized by the addition of alkaline reagents (hydrated lime, limestone, or bag house lime) to water in the open pit; otherwise, more complex treatment measures may be required. Oxidation of soluble ferrous iron seldom is necessary during water treatment in surface mining. Portability of equipment to control alkali additions in water from surface mining sometimes favors use of more expensive reagents such as soda ash or caustic soda. Reliable, controlled addition of solid hydrated lime may be difficult to attain. Proper mixing of the solid reagents must be accomplished, or their effects will be minimal.

Monitoring treated waters to ensure effluent quality should be incorporated into premining planning. Procedures and equipment are available. Maintenance of all water quality control measures is important.

Water Storage

Often topography and/or postmining land use may suggest development of lakes, ponds, or water storage areas. Such procedures have the potential for enhancing land use levels and providing needed water supplies.

BASIC ELEMENTS OF WATER QUALITY CONTROL

The basic elements of water quality control for premining planning are as follows:

1. Acquisition of necessary data regarding:
    a. Surface water flows, elevations, vegetative covers, and surface water quality.
    b. Meteorological data (including a 10-year return frequency and a 24-hour duration precipitation event).
    c. Underground water flows, locations, levels, and quality.
    d. Strata characterization from surface to several feet below the lowest coal seam to be mined (especially permeability and sulfide-carbonate presence).
2. Development of a plan to divert water from area to be disturbed by mining.
3. Collection and handling of surface waters and groundwaters from active mining area.
4. Collection of all area waters for sediment and quality control before effluent release.
5. Design of mining plan from the exploration through reclamation phases to control water quality most efficiently and economically. The plan should take into account slopes and erosion.

SECTION 3

OVERVIEW OF THE MINE DRAINAGE CONTROL PROBLEM

RELATIONSHIP OF GEOGRAPHICAL TRENDS TO WATER QUALITY MANAGEMENT

Of the two principal coal-forming periods in North America, the one that occurred in the central and western states was much later than that in the eastern and southeastern states. The coals on opposite sides of the continent were thus derived from plants of very different types, since considerable evolution occurred in the 150 million years between the Carboniferous and the Cretaceous periods. Moreover, for any geological age, coals were deposited in a number of distinct basins in different parts of the country where they experienced distinctly different geological histories. For these reasons, the coals from the several major deposits have different properties. Of particular importance to water quality management are the various sulfur contents of coals, as shown in Figure 7. This figure shows the known U.S. bituminous reserves as of January 1965, classified by geological province and sulfur content. The presentation shows clearly the predominance of low-sulfur coals in Colorado, New Mexico, Texas, Utah, and Wyoming, and large reserves of medium- or high-sulfur coals in the Illinois-Indiana region and in Missouri, Kansas, and western Kentucky (Haley, 1974).

On a geographical basis, the bituminous coals of northern Appalachia tend, in situ (as opposed to prepared coals), to average about three percent total sulfur. By contrast, the southern Appalachian coals are decidedly lower in sulfur content (approximately one percent). Further to the west, the coals of the interior province increase in total sulfur content, frequently exceeding five percent in Iowa (U.S. Bureau of Mines, 1976). With many exceptions, these in situ total sulfur levels reflect the pyrite content of the coal and associated strata (Lovell, 1975) as related to the geological history of the coals (Williams, 1960; Caruccio, 1972). This is also evident in prepared coals of the several regions (Deurbrouck, 1972), as illustrated in Table 1 (Cavallero, et al., 1976).

The U.S. Bureau of Mines Information Circular 8301 (Walker and Hartner, 1966) gives information on the distribution of pyritic and organic forms of sulfur in a large number of coals from most states of the Union. In low-sulfur coals (<0.6 percent), most of the sulfur (>70 percent) is in the organic form. In coals of higher sulfur content, the proportions of organic and pyritic sulfur are roughly equal, although in some cases there is excess pyritic sulfur.

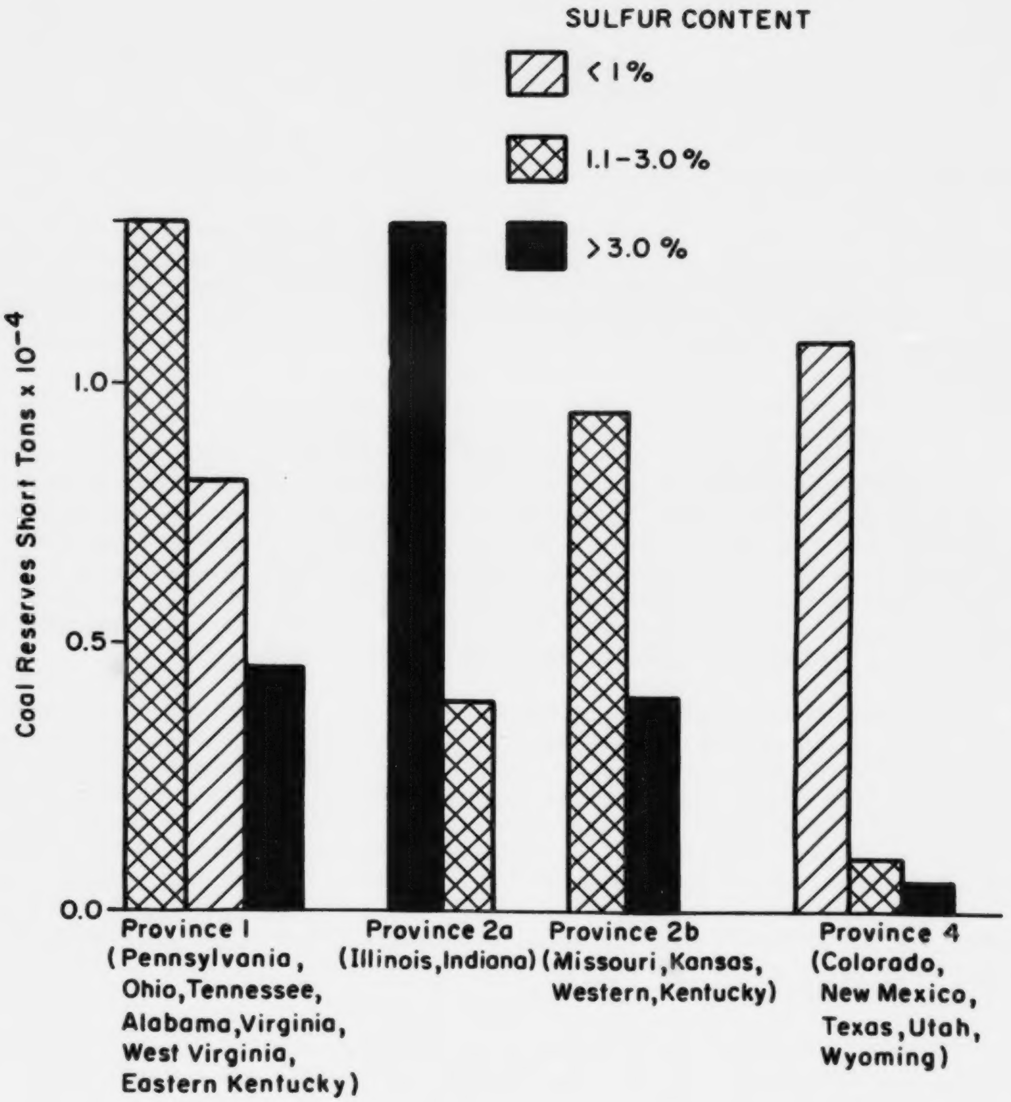

Figure 7. Distribution of U.S. bituminous coals by geological province and sulfur content.

TABLE 1. SUMMARY OF COMPOSITE 1.60 SPECIFIC GRAVITY PRODUCT ANALYSIS, BY REGION*

Region	Cumulative analysis of float 1.60 product						
	Btu recovery (%)	Ash (%)	Pyritic sulfur (%)	Total sulfur (%)	SO_2† (lb/ million Btu)	Calorific content‡ (Btu/lb)	SO_2 removal efficiency required# (%)
Northern Appalachia	92.5	8.0	0.85	1.86	2.7	13,766	56
Southern Appalachia	96.1	5.1	0.19	0.91	1.3	14,197	8
Alabama	96.4	5.8	0.49	1.16	1.7	14,264	29
Eastern Midwest	94.9	7.5	1.03	2.74	4.2	13,138	71

* Source: Cavallero, Johnston, and Deurbrouck, 1976.

† The current allowable SO_2 emission is 1.2 lb per million Btu of coal fired.

‡ The calorific content (moisture-free basis) was used to calculate the SO_2 removal efficiency required.

Removal efficiency required to meet current SO_2 emission standards for the coal crushed to 3/8-in. top size.

Potential water quality changes related to coal characteristics and surface mining are closely correlated with pyrite content and alkaline-mineral content of the coal and associated strata, which are quite different throughout the study region. In eastern coals of the Pennsylvanian age, the confining strata range from more than 50 percent limestone beds in Missouri to less than five percent at the eastern edge, where interbedded sandstone and shale members predominate (Koppe, 1975). More detailed discussion of the occurrence of coal and carbonates is presented in Volume 3 of this study, Geology of Eastern Coalfields.

ORIGIN AND QUALITY OF WATER ENCOUNTERED IN SURFACE MINING

All water reaching a mine site originates from precipitation as rain, snow, or ice, either by gravity flow along the surface of the earth or via percolation through the near-surface strata. The initial quality of this water is characteristically excellent since it has passed through phase changes. The impurities that are later acquired include airborne solids, reacted water soluble gases, and possibly low vapor pressure liquids. Several sources are available for precipitation water quality data, such as the U.S. Geological Survey (Schneider, 1968) and the Geographical Survey for several states. The solubilization of contaminants in precipitation commonly results in water quality changes, especially pH and conductivity. The extent of these changes has large, regional geographical implications reflecting land use (urban, forest, industrial, etc.).

Meteorological Factors

The quality of precipitation, its fluctuating levels, form, frequency, and magnitude are the meteorological factors that influence water encountered in surface mining. These factors partially depend on terrain, land use, and proximity to major water bodies. Basically, the quantity of water to be considered in surface mining is a function of precipitation levels (Hebley and Braley, 1955), whereas the rate at which the water reaches the mine area is modified by elevations, surface cover, soils, and the geologic and hydrologic systems involved. Generalized meteorological data for the study region are available in the publications of the National Weather Service, National Oceanic and Atmospheric Administration, U.S. Department of Commerce. Three publications in particular are of interest: the daily weather reports, the climatological reports, and the daily synpotic weather maps.

These meteorological factors join the geological and phytogenic variables to establish the movement of precipitated waters into two major categories: (1) surface runoff, and (2) percolating groundwater. The water distribution between these categories has major impact on environmental water control in mining. In each case, aspects of flow rate and mineral contact, which are partially subject to man's manipulation, offer the basis for water management.

The Nature of Surface Runoff Waters

Various topographical, geological, hydrological, physical, chemical, and biotic factors interact with precipitation levels to establish the quantity and quality of water entering a mine area. The surface runoff rate is subject to the limited natural control offered by vegetation, and in man-disturbed areas it is partially directed by collection ditches to prevent undesired erosion, sedimentation, distribution, and quality deterioration.

Vegetation of the surface offers the greatest control response to runoff rates. It acts as a water storage mechanism to slow runoff rates but permits continued flow over longer time frames. The clearing of a portion of a forested region before surface mining interrupts a natural surface water distribution format, and unless the changed flow is properly controlled, it can result in severe, short-term area water loading and quality degradation (Figure 8). These actions lead to erosion, stream siltation, localized flooding, interference with the mining operations, and long-range water quality problems. A heavy rain can lead to severe siltation within a very few minutes from haulroads, overburden, and topsoil storage areas. Preferably, siltation control basins should be established before clearing operations begin. Detailed design considerations for erosion control can be found in Erosion and Sediment (Hittman Associates, 1976).

The quality of water runoff from vegetated areas generally shows minimal change, although a washing effect of surface dust coatings as well as vegetation liquids and gases can change water quality. These surface waters may have increased levels of dissolved carbon dioxide, which can enhance the solubility of any carbonate strata contacted and thus increase its alkalinity.

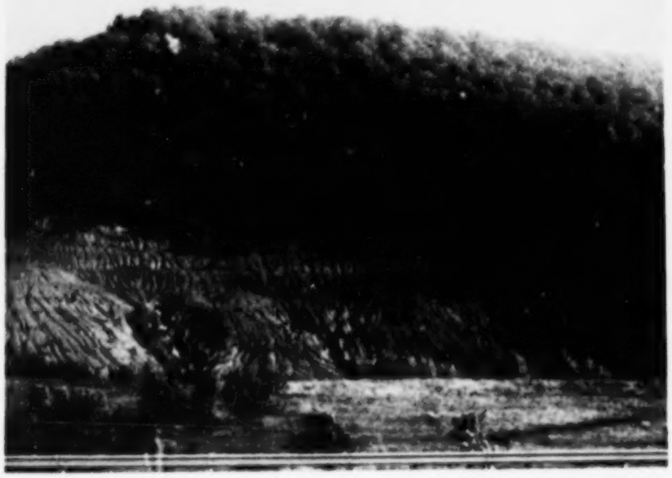

Figure 8. Continuous erosion from a reclaimed surface coal mining operation.

The quantity of water absorbed by vegetation (whether directly or indirectly through the soil) is significant since it will be utilized in the plant metabolism and transpired in part to the atmosphere, thus decreasing the amount of water that would remain in the soil water and groundwater systems.

Water reaching the surface of the earth, whether directly or indirectly from vegetation, will flow or accumulate in response to its rate of release. The rate of this flow is a function of the nature of the surface of the earth, especially elevation variations. At greater flow rates, the energy of flow will have the capability of moving surface particulate matter from one place to another. Particle size, density, and compaction are the major controlling factors in this movement. These surface flows vary greatly in velocity. Levels of erosion usually increase with flow velocity. With a twofold velocity increase, particles of 64-fold mass will be moved, and 32-fold more material will be carried (Buckman and Brady, 1972). These values are suggestions that relate to Stokes' Law and the Newton-Rittinger equation as adapted to sluices and enclosed conduits. Stokes' Law and the Newton-Rittinger equation enable the calculation of the terminal velocity of settling particles. This velocity is a function of the particle size distribution and fluid velocity and viscosity.

Basic surface water flow, which is from higher to lower elevations, eventually forms a streamlet that reaches existing permanent streams. It is the period of time between the first water contact with the surface of the earth and its arrival at a stream that becomes critical in these studies. Because surface mining disturbs the surface and removes vegetation, it will tend to shorten this time frame, thus enhancing the movement of large quantities of particulate matter and increasing solids dissolution by the water flow. These two basic considerations are important in the control of water pollution from surface runoff.

The Nature of Percolating Groundwater

Water that infiltrates the ground surface will continue to move to lower levels at different rates, effectively forming an underground reservoir, where it may flow laterally or vertically. In some geohydrological settings, the attitude and sequence of strata may create an artesian aquifer. The nature of the underground movement of water, including its depth, is primarily a function of its geohydrological setting. This water may be discharged as a free-flowing spring, or it may seep, be consumed by plants, or be pumped from the earth by man. The distance of underground water movement can be extensive (miles), but it is controlled by the surface elevation and permeability of the geologic formations and related hydraulic boundary conditions (see Volume IV of this series, Mine Hydrology). Accordingly, the interactions are not limited to the mine site.

Rate of Infiltration--

Many parameters determine the rate at which water will infiltrate into the strata: soil texture and structure, vegetal cover, biologic residual structures, moisture content of the soil, physical condition of the surface, water quality and temperature, etc. (Thornbury, 1969; Taylor and Ashcroft, 1972). Infiltration capacity decreases exponentially in time from a maximum to a slower constant rate approaching a saturated condition. The saturation and infiltration rates may be modified by swelling of clay particles. Surface runoff increases when precipitation intensity exceeds infiltration capacity, unless there is a localized geological discontinuity.

Various surface discontinuities such as faults, zones of fracture concentrations underlying lineaments and fracture traces, and joints represent localized regions of enhanced strata permeability and subsurface flow. Changes in localized groundwater flow systems caused by surface mining pose great difficulties in surface mine water control. The original near subsurface aquifer system is disturbed, and a new system will eventually be established upon completion of the mine restoration. The replaced system is characteristically more porous and homogeneous, despite compaction efforts.

It is the time frame of contact and the interactions of the groundwater with the subsurface strata that constitute the major considerations of water quality control in mining. This most critical factor concerns the effects of water movement and subsequent changes in water quality that occur during and after mining and that would not have otherwise occurred.

Natural Beneficiation--

Naturally occurring phenomena that change surface mine water quality are termed "natural beneficiation." The effects of these phenomena can be utilized as water quality control measures (Lachman and Lovell, 1970). Natural beneficiation may involve the diversion of surface or groundwaters, or it may achieve the mixing of alkaline and acidic waters from several sources. Such mixing may result in dilution, dissolution of solids, or reactions between water components to improve quality, form insoluble substances, or result in physical absorption of certain water components on other surfaces.

Mineral Solubility--

The quality of groundwater is primarily controlled by (1) solubility of minerals and transportation of insoluble substances contacted by the waters on the surface, (2) the solution of minerals and organic matter contacted by the soil water and groundwater, and (3) the quality of precipitation that may enhance the solution of some carbonate materials. In addition to direct dissolution of minerals or their components, chemical reactions may occur among the water, air, and biotic population that can alter mineral composition and result in greater water solubilities. Potential also exists for ion exchange activity among percolating waters, soil components, and various minerals, which can cause changes in water quality. Thus the mineralogy of coal-bearing and associated strata is important in determining potential water pollution problems. Once a groundwater has achieved a characteristic composition from mineral solubilization, its capacity as a lixiviant may be enhanced, increasing the potential for further reaction when mixed with any other groundwater or contacting other strata.

Carbonates--The most water soluble mineral components commonly encountered in coal measures are the carbonates, which add calcium, magnesium, carbonate, and bicarbonate ions to the waters, generally raising the pH, the alkalinity, and the buffering capacity. Some vegetation may introduce carbon dioxide and/or natural organic acids into the water, which may lower its pH but at the same time increase its ability to dissolve carbonates.

Commonly, water that contacts coal strata or coal products (such as in a preparation plant) will dissolve small concentrations of mineral and coal components (humic acids, for example). But this process has negligible effects on water quality other than increasing its total dissolved solids and conductivity (Lovell and Reese, 1965). However, these dissolved solids may increase the lixiviant characteristics of the percolating waters to dissolve carbonates, clays, etc. Alkaline water may decrease the undesirable pollutant loading by reducing the tendency for pyrite oxidation directly (Barnes and Romberger, 1968) or by inhibiting bacterial activity (Lorenz and Tarpley, 1963).

Pyrite--The most obvious source of coal mine drainage pollution is the mineral pyrite, which occurs in varying amounts in all coal measures. Another iron sulfide mineral, marcasite, is usually considered a less significant source because of its less frequent occurrence in coal-bearing strata. Pyrrhotite and troilite (FeS) are rare in coal measures.

Various other iron or sulfate minerals such as melanterite, $FeSO_4 \cdot 7H_2O$; coquimbite, $Fe_2(SO_4)_3 \cdot 9H_2O$; halotrichite, $FeAl_2(SO_4)_4 \cdot 22H_2O$; capiopite, (Fe, Mg) $Fe_4(SO_4)_6(OH)_2 \cdot 20H_2O$; alunogenite, $Al_2(SO_4)_3 \cdot 18\,H_2O$; gypsum, $CaSO_4 \cdot 2H_2O$; and siderite, $FeCO_3$ are generally believed to be of secondary origin and are usually present at insignificant levels in coal measures.

Coals also contain sulfur in the organic form, originating with the parent vegetal coal source. These substances do not contribute to coal mine drainage formation or water pollution.

There does seem to be a direct relationship between the pyritic sulfur level of coal and existing water pollution levels, but there are many extraneous factors that create deviations. Before significant pollution levels are attained, the pyrite must be oxidized to water soluble substances. Thus the rate of this oxidation becomes critical.

Frequently, the existence of pyrite concentrations in strata above or below a coal seam is ignored as a pollution source, though they may be the major offending source. Pyrite may also be found in limestone, sandstone, and shale associated with coal seams (Hanna and Brant, 1971; Newhouse, 1927), where it commonly occurs in distinct bands or lenses at very high concentrations.

Factors Affecting Pyrite Oxidation and Solubilization. Among those factors affecting the ease of pyrite oxidation and solubilization are size (Caruccio, 1970), distribution and concentration of pyrite grains, ease of contact between pyrite grains and water, pyrite/water contact time, surface area of pyrite particles, crystallinity of pyrite, and purity of pyrite grains (Caruccio, 1972).

Water quality factors impinging on pyrite oxidation and solubilization include pH, Eh, ionic strength, and concentrations of dissolved oxygen, acidity, alkalinity, carbonate, bicarbonate (Caruccio, 1968), total dissolved solids, ferrous iron, and ferric iron. Physical factors include temperature, water flow rates, extent of agitation, aeration, pressure, presence of sediment, minor soluble components (Hem, 1960), density variations, and depth of flows and channels. There are also pronounced effects from autotrophic bacteria.

In natural waters with pH levels above 4.8, soluble ferric species seldom exceed 0.01 mg/ℓ unless complex ions are present. Colloidal ferric hydroxide is common to surface waters, even when they appear quite clear.

Reactions Resulting in Pyrite Solubilization. The chemical reactions commonly cited to describe the formation of coal mine drainage are:

a. $FeS_2 + 3\ O_2 \longrightarrow FeSO_4 + SO_2$
b. $2\ FeSO_4 + 1/2\ O_2 + H_2SO_4 \longrightarrow Fe_2(SO_4)_3 + H_2O$
c. $FeS_2 + Fe_2(SO_4)_3 + 8\ H_2O \longrightarrow 3\ FeSO_4 + 2\ H_2SO_4 + 12\ H^+$
d. $2\ SO_2 + O_2 \longrightarrow 2\ SO_3$
e. $SO_2 + H_2O \longrightarrow H_2SO_3$
f. $SO_3 + H_2O \longrightarrow H_2SO_4$
g. $Fe_2(SO_4)_3 + 3\ H_2O \longrightarrow Fe_2O_3 + 3\ H_2SO_4$

The initial step involves the oxidation of pyrite to several water soluble components, and thus the limiting factors are those variables that control this oxidation reaction. Obviously, the water solubility of these reactant and product substances is critical to the problem. Solubility levels are detailed as follows:

FeS_2	4.9×10^{-5} g/ℓ (Handbook of Chemistry and Physics, 1952)
$FeSO_4$	2.08×10^{2} g/ℓ (20°C) (Linke, 1965)
$FeO(Fe(OH)_2)$ . . .	1.5×10^{-5} moles/ℓ (25°C) (Linke, 1965) [equivalent to 2.43×10^{-3} g/ℓ]
$Fe_2O_3(Fe(OH)_3)$ . .	3.4×10^{-10} moles/ℓ (20°C) (Linke, 1965) [equivalent to 9.08×10^{-8} g/ℓ]
$FeCO_3$	72 g/ℓ (18°C - 1 atmosphere CO_2) (Linke, 1965)
$Fe(SO_4)_3$	Occurs in several phases (Linke, 1965): $Fe_2O_3 \cdot 2.5\ SO_3 \cdot 7\ H_2O$ $Fe_2O_3 \cdot 3\ SO_3 \cdot 9\ H_2O$ $Fe_2O_3 \cdot 4\ SO_3 \cdot 9\ H_2O$ $Fe_2O_3 \cdot 3\ SO_3 \cdot 8\ H_2O$ (Solubility ranges from 0.3 to 205 g/ℓ for Fe_2O_3 and from 35.5 to 568 g/ℓ for SO_3.)

These and related reactions proceed at widely varying rates and in varying orders, developing for each location some type of equilibrium as established by the prevailing physical, chemical, and meteorological conditions. However, the typically unsteady state conditions above and below ground create a most complex system. It has been suggested that pyrite serves as a catalyst for the oxidation of sulfur dioxide and the sulfite ion (Reaction d).

Reaction g results in a deposition of hydrous iron oxide but allows sulfate species to remain in solution. The hydrous iron oxides coating stream bottoms and streaking coal and other strata are indicators that coal mine drainage was formed (Figure 9). Detailed study of these precipitated deposits (Whitemore, 1973), often termed "yellowboy," has been made. Field stability diagrams (Hem, 1970) show the stable equilibrium forms of iron (Figure 10) and manganese (Figure 11) at various combinations of Eh and pH in the environment.

Crystallization pressures of secondary minerals are thought to perpetuate acid production by mechanical destruction of the pyrite-containing strata. Although effective pressures encountered in practice generally range between 0.1 and 0.01 times theoretical crystallization pressures, these are often sufficient to disrupt rocks containing reactive pyrite (Koppe, 1975; Winkler and Singer, 1972).

Figure 9. Aquifer drainage from highwall of Pennsylvania surface coal mine.

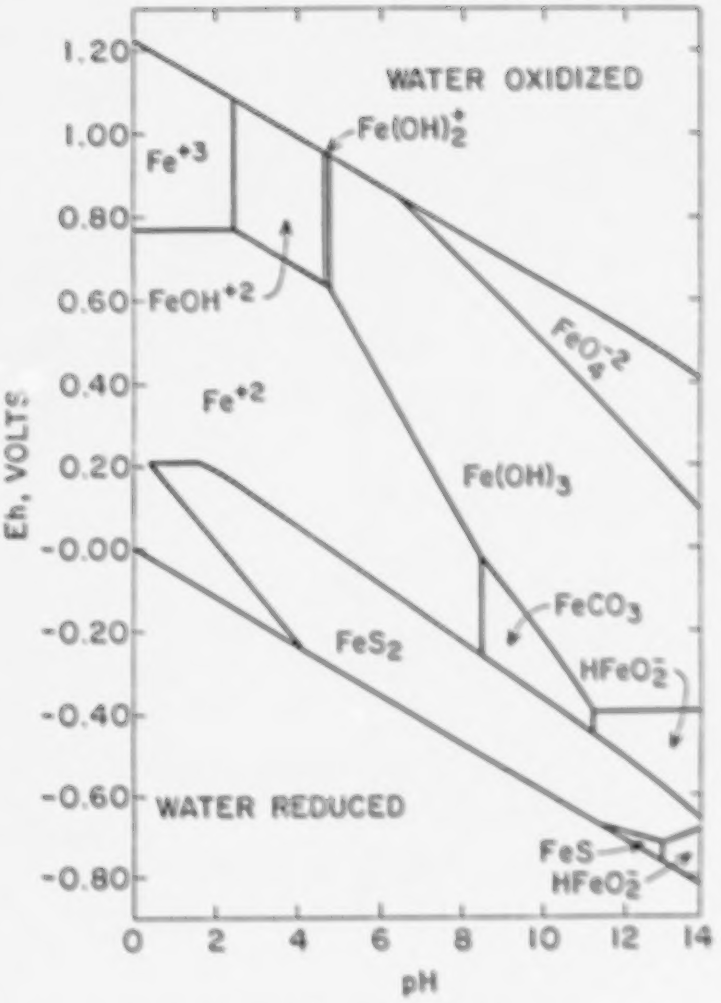

Figure 10. Fields of stability for solid and dissolved forms of iron (Hem, 1970).

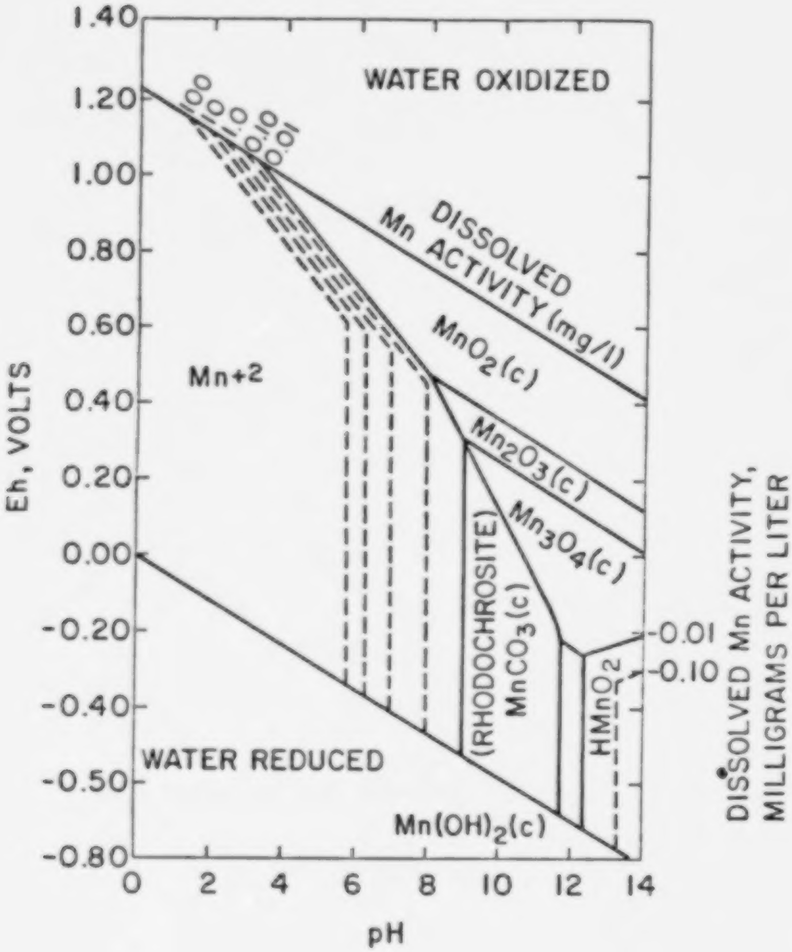

Figure 11. Fields of stability for solid and dissolved forms of manganese (Hem, 1970).

Oxygen can reach the pyrite surface either in the gaseous phase or dissolved in percolating groundwater. Even in dry mines and strata, pyrite oxidation can occur, since any air circulation will carry water in the gaseous state as humidity.

The item of concern after formation of water soluble products from pyrites is their rate of entry into the effluent streams after contacting the mineral surfaces. This rate depends on (1) flushing by a rising water table, (2) water percolation through open channels and pores, and (3) the diffusion of saturated solutions as a result of lowered vapor pressure.

Smith and Shumate (1970) have suggested that the development of some ferric ion in chemical mine drainage (CMD) favors higher rates of pyrite oxidation by Reaction c.

Contact of alkaline groundwaters with surface-oxidized pyrite may form ferrous bicarbonate and basic ferric sulfates. Although such waters may tend to minimize further pyrite oxidation, they frequently achieve a net acidity before discharge from the mine.

Pyrite Oxidation. Since the oxygen diffusion rate (Smith and Shumate, 1970) in water is much slower than in air (x 10^{-4}), it is assumed that vapor state transportation of oxygen generally prevails. Upon contact of oxygen at the pyrite surface, a reaction site is formed. The oxygen concentration gradient in a particular stratum depends on (1) strata porosity (void volume and its continuity), (2) exposed pyrite surface area/unit volume of strata, and (3) order of pyrite oxidation reaction. The oxygen diffusion mechanism will define the location of the pyrite reactive sites as they are exposed to vapor and not submerged under more than 0.25 in. of water.

The rate of pyrite chemical oxidation may be limited either by the reaction rate itself or by the reactant (oxygen) transport rate. In environments of less than two percent O_2, the rate is first order and predominantly chemical (Smith and Shumate, 1970). The depth of reaction (pyrite oxidation) into the strata depends on oxygen diffusion (and thus really depends on strata porosity).

Silica--Silica is found in most groundwater up to about 30 mg/ℓ (and occasionally to 100 mg/ℓ), varying with rock type and temperature. Various clay minerals, residual quartz, or feldspars are common sources of silica. Generally, solubility of silica is very low; but above pH 9.0, it may increase rapidly (Davis and DeWiest, 1966). Undesirable interactions may occur between dissolved silica and aluminum species.

Aluminum--Among the mineral solution strata reactions, conditions may occur that favor extensive solubility of aluminum, presumably from clays or shales. Aluminum is probably the most important of the metallic cations found in coal mine drainage other than iron, as it creates acidic responses in solution similar to iron ion species, and it can also create difficulties during coal mine drainage treatment. Aluminum has seldom been described as an obnoxious component of coal mine drainage, although it can be quite toxic to some plants. The availability of aluminum in groundwaters is related to cation exchange capacity of the soils and strata as well as pH, ionic strength, and the occurrence of soluble ions in the water (Brady, 1974; Tisdale and Nelson, 1975). Aluminum is an unusual contaminant of groundwater unless the pH is low (4.0), when it may occur as Al $(OH_4)^-$. When dissolved silica occurs in groundwater, the polymerization of aluminum hydroxide proceeds in a unique fashion. For waters whose pH is below 4, aluminum solubility has been estimated from the solubility product for gibbsite ($Al(OH)_3$), which is soluble in sulfuric acid. Gibbsite, though not common to coal measures, is a likely alteration product of kaolinite (a common coal measure clay mineral) by silica solubility.

Manganese--Manganese found in coal mine drainage may originate either from isomorphic substitution in iron sulfides or trace levels of manganese minerals in the coal strata as pyrolusite (MnO_2), psilomelane ($MnO \cdot MnO_2 \cdot 2H_2O$), rhodochrosite ($MnCO_3$), or even manganite ($Mn_2O_3 \cdot H_2O$). It is not unexpected for some form of manganese to occur in coal measures, since this element is essential in plant metabolism as a minor nutrient. The oxidation of Mn^{+2} and subsequent precipitation of MnO_2 increases with pH and surface area. Bacteria are also known to influence the rates of manganese oxidation.

Manganese is normally present in coal drainage waters as the Mn^{+2} ion, whose solubility increases as the pH falls below 7.0. The ion pair $MnSO_4$ has been reported in waters containing high sulfate concentrations and may exist in coal mine drainage. Manganese is difficult to remove from waters to levels below the 1 mg/ℓ unless a high pH is maintained. The Eh/pH diagram of Mn (Figure 11) illustrates these aspects (Hem, 1970).

Trace metals--Other elements in very low concentrations, such as chromium, zinc, and cadmium, are not uncommon in coal mine drainage and are considered acutely toxic. Studies of such occurrences have been increasing in frequency (Rao and Gluskoter, 1973; Ruch, et al., 1973). No extensive studies have been made regarding their removal by treatment processes, but there has been regulatory consideration for the establishment of effluent standards.

Mineral solubilization by autotrophic soil bacteria--There is little doubt that autotrophic bacteria, specifically *Thiobacillus ferrooxidans* and similar genera (Buchanan and Gibbons, 1974), play a major role in both the oxidation of pyrite and of solubilized ferrous sulfate (Reactions a and b) (Lorenz and Tarpley, 1963). These organisms utilize iron and sulfur in their metabolism, and since they are aerobic, they draw their oxygen from the air as well as use airborne carbon dioxide as a carbon source. They grow optimally at pH levels near 3.0, whereas other species may metabolize at higher pH values. They are relatively common soil bacteria, and they frequently reach population densities exceeding 10^6 cells/ml.

LEGAL ASPECTS OF MINE DRAINAGE CONTROL

Government Regulations

The legal status and government regulation (Federal and State) of water pollution in general and that associated with coal mining ranges from the Sanderson case in 1886 (Wright and Bauman, 1943) to the recently promulgated (April, 1977) EPA guidelines (Coal Mining Guidelines and Standards, 1977) and the Bureau of Land Management Coal Mining Operating Regulations (1976). The effluent limitations under the Clean Water Act of 1977 (P.L. 95-217), Title 40, Part 434 (Coal Mining Point Sources) for best practical control technology currently available are shown in Table 2. Effluent guidelines are also mandated under the Surface Mining Control and Reclamation Act of 1977 (P.L. 95-87).

Exceptions provide for the 10-year, 24-hr precipitation event and for drainage from surface mines that have been returned to final contour, providing such drainage has not been comingled with untreated mine drainage that is subject to limitations.

These effluent guidelines also include the proposals for best available technology economically achievable, subject to future promulgation.

The national pollutant discharge elimination system (NPDES) (Schaffer, 1975) established a pollution elimination goal from point sources for navigable waters by July 1983, which charges the EPA with protection and maintenance of water quality. This goal is to be achieved by a national

TABLE 2. EFFLUENT LIMITATIONS UNDER TITLE 40, PART 434, OF THE CLEAN WATER ACT OF 1977 (COAL MINING POINT SOURCES)

Item	Daily maximum	Daily average over 30 days
Subpart C, Section 434.30 - 434.32 (Acid or Ferruginous Mine Drainage):		
Iron, total (mg/ℓ)	7.0	3.5
Manganese, total (mg/ℓ)	4.0	2.0
TSS (mg/ℓ)	70.0	35.0
pH	6.0 - 9.0	----
Subpart D, Section 434.40 - 434.42 (Alkaline Mine Drainage):		
Iron, total (mg/ℓ)	7.0	3.5
TSS (mg/ℓ)	70.0	35.0
pH	6.0 - 9.0	----

permit system (NPS) and stream quality standards (P.L. 87-88, 1961), in conjunction with State regulations (Commonwealth of Pennsylvania, 1937). Available guidelines for the coal industry (Coal Mining Effluent Guidelines and Standards, 1977) cover only best practical control technology currently available. Yet to be released by EPA are guidelines for best available technology economically achievable and toxic pollutants, new source performance standards, pretreatment standards, and the identification of control measures and practices to eliminate the discharge of pollutants. The permits, granted for periods up to five years, cover deep and surface coal mines and preparation plants. They may incorporate special provisions, self-monitoring requirements (in conjunction with State requirements) for pH, concentrations of iron, acidity, and suspended solids, and effluent limitations (daily average and maximum)--all based on the industry guidelines, including modes of sampling and analysis. Permit time limits are usually associated with release of State reclamation bonds. Any State may impose additional or stricter regulations, which then become a Federal requirement of the permit.

According to the Permanent Regulatory program of the Surface Coal Mining and Reclamation Operations under the Surface Mining Control and Reclamation Act of 1977 (P.L. 95-87, Title 30, Chapter VII, Subchapter K, Section 816.42), all drainage from the area disturbed by surface mining, including disturbed areas that have been graded, seeded or planted, shall be passed through a sedimentation pond or a series of sediment ponds before leaving the permit area. Sedimentation ponds and other treatment facilities shall be maintained until the disturbed area has been restored and the revegetation requirements are met and the quality of the untreated drainage from the disturbed area meets the applicable State and Federal water quality standards requirements for the receiving streams.

A bypass provision may be developed for a major precipitation event (to 6 hr after the event), and thus regulations are excluded during that period. The discharger must be able to prove that such an event occurred if questioned.

Other Legal Considerations

Conflicts over water rights are usually resolved in common law courts using the property system and the doctrine of nuisance. A water right is a property right and is entitled to the same extent of protection as other forms of property. A water right is a usufructuary right to the flow and use of water. The water is generally considered to remain common property until it has actually been diverted from its natural course and reduced to private possession by means of artificial devices (Thomas, 1955).

The law of water rights embraces two diametrically opposed doctrines and numerous modifications and combinations of those doctrines (Thomas, 1955). In many states, water rights are based on ownership of land contiguous to a stream or other source, or overlying a groundwater reservoir (land ownership rights); the right does not depend on putting the water to use, and thus it is not lost by nonuse. However, in some States, water rights are based entirely on appropriations and actual use of water that has been declared to belong to the public (appropriative rights). Such rights are based on priority in time, and they may be forfeited if the water is allowed to go unused for a specified period. But ownership of land is not essential. In the remaining states, both these doctrines or modifications thereof are accepted, and each applies to certain classes of water or to certain conditions of development. Figure 12 shows areas of the United States with moisture surplus and deficiency and indicates the basis of water rights in various states (Thomas, 1955). As the map indicates, the Appalachian and eastern interior coal basins fall strictly under the riparian doctrine or land ownership basis of water rights, whereas the western interior basin employs a combination of appropriative and land ownership rights. A summary of water rights and their legal consequences for the States that make up the Appalachian region and the eastern and western interior regions is provided in Tables 3 through 5 (National Water Commission, 1973).

Riparian Rights--

Under the concept of riparian rights, the owner of land adjacent to a stream (riparian land) is entitled to receive the full natural flow of the water without change in quality or quantity. No upstream owner may materially decrease or increase the natural flow of a stream to the disadvantage of a downstream owner. A number of modifications have been made to this doctrine over the years to permit reasonable use of waters. The major modifications as presented by Linsley et al. (1968) are listed as follows:

1. Reasonable Use - A man's right to use water on his own land must be restricted to a reasonable use in view of the similar rights of others. Reasonableness of use is usually determined by such factors as area, character of the land, importance of the use, and possible injury to other riparian uses.
2. Correlative Rights - Wherever landowners have rights in a common water supply that is insufficient for all, each is to receive a fair and just proportion.

Other important aspects of riparian rights include:

1. An upstream proprietor may always use as much water as he needs for domestic use and for watering domestic stock. Such use is considered an _ordinary_ or _natural_ use.
2. Irrigation water used for mining facilities or watering of commercial herds of stock is an artificial use.
3. Riparian rights can be lost by upstream adverse use that ripens into a prescriptive right at the end of the period specified under the statute of limitations.
4. If a parcel of riparian land is divided, any section not adjacent to the stream loses its riparian status unless the right is specifically preserved in the conveyance.
5. Riparian rights do not attach to land outside of the stream basin, even though such land is contiguous to riparian land in the basin.

Appropriative Rights--

The basic concept of the doctrine of appropriation, or Colorado doctrine, is that the landowner has no inherent right to use water from sources upon,

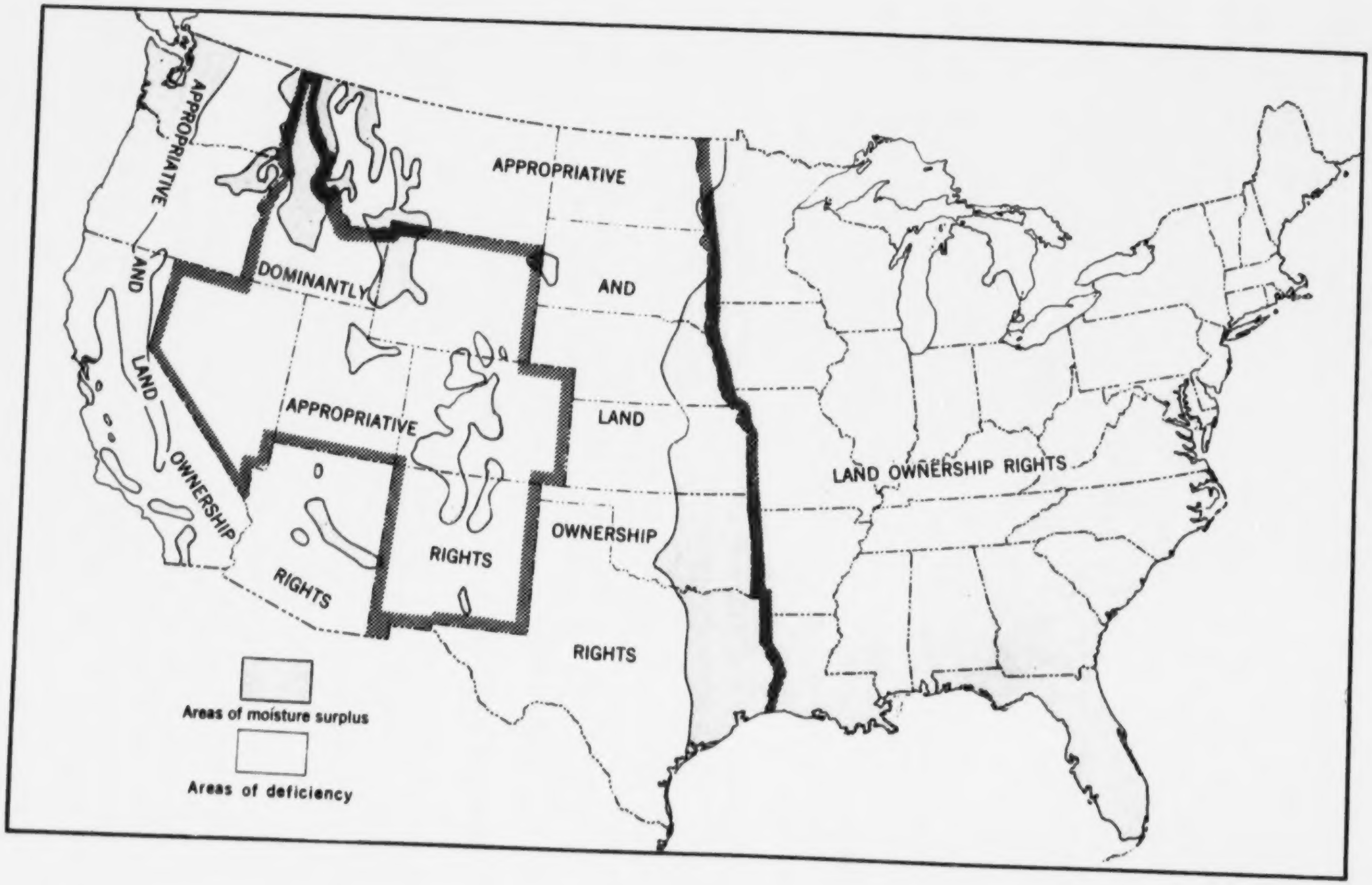
APPROPRIATIVE
AND
LAND
OWNERSHIP
RIGHTS
DOMINANTLY
APPROPRIATIVE
RIGHTS
APPROPRIATIVE
AND
LAND
OWNERSHIP
RIGHTS
LAND OWNERSHIP RIGHTS
Areas of moisture surplus
Areas of deficiency

Figure 12. Areas of moisture surplus and deficiency in the United States and the basis of water rights in various States (Thomas, 1955).

TABLE 3. SUMMARY OF WATER RIGHTS FOR THE APPALACHIAN REGION[*]

State	Extent of existing law[†]	Comments
Ohio	Limited to water quality control, water use planning, the regulation of dam construction, and drilling of water wells.	State has no statutory procedure governing the acquisition, distribution, or transfer of water rights. Conflicts are resolved by the courts in private litigation on a case-by-case basis and judged by the principle of reasonable use. Primarily rights of usage are for domestic purposes and municipalities in Ohio situated on a natural stream, and considered riparian proprietors may supply water to all of its inhabitants. The Water Pollution Control Board is responsible for issuing discharge permits.
Pennsylvania	Permit system to control water use by public water and power supply agencies and has a number of statutes designed to protect navigation, to improve water quality and to conserve and use water in accordance with balanced water planning.	Little State administrative control in the areas of water rights. Riparian water rights and uses are not administered but are subject to certain regulations, such as water quality standards and navigational controls. Conflicts are settled in the courts, and relief is rewarded in the way of an injunction to prevent interference with the land owner's water right or money damages for unlawful injury or impairment to water rights or uses. In 1971, the Department of Environmental Resources was formed, and it has responsibility for water resources, outdoor recreation, and water pollution. It also implements the PA Clean Stream Act based on a permit system, can call for payment by a water user "in lieu of" cleaning the user's discharge if the State feels the funds would serve the public welfare more.

(Continued)

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[*] Source: Adapted and modified from National Water Commission, 1973.

[†] All water rights doctrines used are riparian.

TABLE 3. (Continued)

State	Extent of existing law	Comments
Maryland	Based on a permit system which (1) permits for the rights to appropriate or use both surface & groundwater and (2) permits for construction of reservoirs, dams and waterway obstructions.	State operates under 1934 legislation setting up permit system. The Department of Water Resources controls State permit system. 1970 law repealed old water pollution laws and expressly preserved the right of riparian owners to suppress nuisances or to abate pollution in equity or under common or statutory law. The Act also made it unlawful to pollute State waters. Violators may have a hearing or have to submit a report, and they can be sued.
West Virginia	Very limited; there has not been extended treatment by either courts or legislation.	Most problems in the past have centered around the disposition of excess water rather than conflicts over use of existing supply. Where conflicts have arisen, the courts have adopted the reasonable use doctrine of riparian water rights. Although there is very little State administrative control over water rights, there is a Division of Water Resources that takes inventories of resources, formulates comprehensive plans and makes recommendations for protection. West Virginia Water Pollution Control Act states that it is public policy to maintain reasonable standards of purity & quality.
Virginia	Regulation is largely confined to navigation, fisheries, shellfish, and flood control.	Problems have been increasing because of the competition of water in the coastal plain. A need for some kind of regulatory or permit system has been identified. Disputes are settled in the courts on a case-by-case basis (under reasonable use doctrine). 1970 Water Control law regulates water quality through State Water Control Board.

(Continued)

TABLE 3. (Continued)

State	Extent of existing law	Comments
Kentucky	In 1966, the legislature passed legislation that provides for a limited amount of State administrative control over the utilization and allocation of the waters of the State. All other rights are riparian and subject to reasonable use.	Conflicts are solved in the courts on a case-by-case basis. There is a State Water Pollution Control Commission which oversees and issues permits to discharge wastes of other matter into State water. It also has emergency powers to protect the public health.
Tennessee	General lack of legislation on water rights.	Tennessee courts apply reasonable use doctrine of riparian rights and the reasonable use principle. There is virtually no State administration of water rights. There is a Water Quality Control Board that regulates water quality and pollution by the issuance of permits.
Alabama	Legislation has been confined to drainage and pollution problems.	Water use conflicts are regulated in private litigations by reasonable use doctrine. There are no State administrative units to regulate use, but State Water Improvement Commission controls water quality and pollution; flood plains are also regulated.

TABLE 4. SUMMARY OF WATER RIGHTS FOR THE EASTERN INTERIOR REGION*

State	Extent of existing law†	Comments
Illinois	There are some statutes in Illinois regulating the manner in which water may be used. However, there is no comprehensive legislative effort to provide State administrative control over water use or rights.	Water rights are incidental to ownership of land abutting a stream apart from statutory regulations and control over water quality by a couple of State agencies. The rights of the riparian land owner extend to quality as well as quantity; conflicts are decided on the principle of reasonable use.
Indiana	Law has developed slowly and is not extensive.	Indiana law is not fully defined but seems to be based on the reasonable use doctrine of riparian rights. In recent years, the legislature has enacted legislation for the control of water pollution and has adopted limited administrative controls relating to the right to use surface and groundwater. The Dept. of Conservation controls groundwater withdrawals and the Flood Control and Water Resources Commission regulates surface water. In 1955 the legislature declared surface water to be public waters and controlled by the State.
Kentucky	In 1966, the legislature passed legislation that provides for limited State control over the use and allocation of waters. All other rights are riparian and subject to reasonable use	Conflicts are solved on a case-by-case basis. There is a State Water Pollution Control Commission that issues permits to discharge wastes into State waters and exercises emergency powers to protect public health.

* Source: Adapted and modified from National Water Commission, 1973.
† All water rights doctrines used are riparian.

TABLE 5. SUMMARY OF WATER RIGHTS IN THE WESTERN INTERIOR REGION*

State	Water rights doctrine used		Extent of existing law	Comments
	Riparian	Appropriation		
Missouri	X		There is little decisional law relating to groundwater. However, the same rules that govern underground streams also govern surface water.	There is no statutory regulation governing the acquisition, administration, or distribution of water. Conflicts over water rights constitute a judicial decision area based on the riparian doctrine. In 1961, the State stepped toward water resource planning by creating a Water Resources Board. This is a comprehensive planning board. Pollution is regulated by the Water Pollution Board, which carries out enforcement procedures against violators.
Kansas		X	Unallocated water is subject to appropriation, but all prior rights - whether appropriation or riparian - are preserved and protected. General administration of water rights is under State control and legislation.	General administration of water resources is with Division of Water Resources. A right can be initiated only by filing application with the chief engineer. In conflicts, domestic uses are privileged. A Water Quality Control Act is administered by the State Board of Health. The Water Resource Board provides for comprehensive water resource planning.

(continued)

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*Source: Adapted and modified from National Water Commission, 1973.

TABLE 5. (Continued)

State	Water rights doctrine used		Extent of existing law	Comments
	Riparian	Appropriation		
Oklahoma	X	X	State is basically appropriative, but riparian rights still exist. Statutes provide for administrative control and regulation of State waters.	Oklahoma Water Resources Board developed State Water plans to insure best resource planning. State is divided into water districts. To initiate a water right, one must file an application with this board. Anyone having a right to use, but impaired from that use, may file suit in district court. Water quality is regulated by Water Pollution Control Act administered by the Water Rights Board. Appropriation rights may be obtained through the Water Rights Board, pursuant to the relevant statutory procedures, and riparian rights for domestic use may be acquired by acquiring riparian land.
Arkansas	X		Law is not extensive except for law on diffused surface water and water on watercourse.	Riparian doctrine is followed except for the allocation and distribution of surplus water. Conflicts are resolved in the courts, but more State regulation could come about in the future. Water quality is regulated by the State Soil and Water Conservation Commission

contiguous to, or underlying his land, but that rights to these sources are based on priority in time of beneficial use and may be lost after the use ceases (Thomas, 1955). In common usage, an appropriator is one who takes exclusive possession of an article that has been recognized as common property or that has been owned by others. Depending on the reactions of the true owner, the courts may consider this act to be unlawful and criminal, or they may legitimize it by reason of either long-continued adverse use or the owner's consent.

The appropriation doctrine provides for acquiring rights to the use of water by diverting it to beneficial use in accord with procedures that are set forth in State statutes or acknowledged by the courts. Appropriated water may be used on lands away from the stream as well as on lands adjoining the stream. The earliest appropriator in point of time has the exclusive right to the use of water to the extent of his appropriation without reduction of quantity or deterioration of quality whenever the water is naturally available. Each subsequent appropriator has like priority over all appropriation later in time than his own. Appropriations are for a definite quantity of water and are valid as long as the right is exercised. Appropriations may be made only for beneficial and reasonable uses.

Drainage Law--

The laws applicable to the disposal of storm runoff waters are also of concern to mining operations. These laws apply to modification of natural surface drainage patterns, and to date they have been applied principally to urbanizing areas. However, inasmuch as surface mining operations can substantially alter the existing surface drainage patterns and consequently the total volume of storm runoff for a given watershed, drainage law becomes a concern of the mining engineer.

Two basic legal approaches have found widespread use in the United States, namely, the Roman civil law and the common-enemy rule (Linsley et al., 1968). The following list indicates the rule that is followed in various states:

Roman civil law:

- Alabama
- Georgia
- Illinois
- Iowa
- Kentucky
- Maryland
- Michigan
- North Carolina
- Ohio
- Pennsylvania

Common-enemy rule:

- Arkansas
- Indiana
- Kansas
- Missouri
- Nebraska
- Oklahoma
- South Carolina
- Tennessee
- Virginia
- West Virginia

Roman civil law specifies that the owner of high land (dominant owner) may discharge his drainage water onto lower land through natural depressions and channels without obstruction by the lower or servient owner. The dominant owner can improve and speed up the flow of surface water by constructing drainage conveyances such as ditches or by making improvements to existing channels. However, he may not carry water across a drainage divide and discharge it on land that would not have received the water naturally, nor may he locate the outlet of his drainage system at a point other than the natural outlet of the area. On the other hand, the servient owner can do nothing to prevent drainage from entering his property from above.

The basic principle underlying the common-enemy rule is that water is a common enemy of all, and any landowner may protect himself from water flowing onto his land from a higher elevation. According to this approach, a dominant landowner may not construct drainage works that result in damage to the property of a servient owner. Thus a drainage easement must be secured from the servient owner to discharge surface runoff through his property. The servient owner is allowed to construct dikes or other works to prevent the flow of surface water onto his property.

Both of these legal approaches to drainage practice place the responsibility for damages on any person or organization altering the natural stream pattern of an area or creating an obstacle that blocks the flow of a natural stream.

SECTION 4

COMMON APPROACHES TO MINE DRAINAGE ABATEMENT AND WATER QUALITY CONTROL

CONTROL OF WATER MOVEMENT

In surface mining, the prevention and control of water quality degradation and any necessary treatment of mine drainage require premining planning, diversionary actions during site and mine preparation, constant monitoring and action during mining, and water movement control during backfilling and surface reclamation operations. The control of water movement may involve any one or a combination of three basic water management approaches, which include: (1) surface flow control, (2) soil water control, and (3) strata dewatering. The objective of these management tools is simply to divert the flow of waters from the mine area and thus, through isolation, to reduce the opportunity for water quality deterioration. Premining evaluation of these water flows and qualities is critical, including establishment of regions of higher water permeability.

The water management approaches discussed in this section are presented because they appear to be applicable under many hydrogeological and geochemical circumstances. But because not all have been adopted by the industry, published documentation of costs and benefits are not always available. Actual strata dewatering and, particularly, the control of potable and polluted mine waters using largely mechanical schemes (i.e., connector wells and disposal wells) have not been adequately demonstrated in the mining applications to date.

Control of Water Movement as Related to Water Quality

The source of waters and their flow contacting coal-related strata have been discussed in Volume 4, Mine Hydrology. The initial concern is to establish before mining (1) the potential amounts and sources of waters (precipitation, surface runoff, and interception of aquifers), (2) flow direction, and (3) characteristics (such as quality) that may be encountered during mining. These variables must be correlated with localized conditions to suggest potential factors indicative of water quality degradation. Previous mining history of the immediate area should be established to indicate potential interception of abandoned deep mines and/or auger mining channels or other natural conditions that could affect water quality. Detailed drilling may be necessary.

The first consideration is the control of surface water flow by diversion ditches around and within the disturbed site. Special diversion is often helpful above and around the designed highwall. Surface streams may be encountered (sometimes only with seasonal flow) for which it may be necessary actually to divert a stream channel. Such streams must be evaluated for regions of high bottom infiltration potential because they may be a source for recharging underground aquifers and may thus have the potential for introducing large volumes of water into the active pit during mining. These zones of high permeability may be related to major concentrations of fractures, joints, faults, or outcrops. The use of stereo aerial photographs and detailed local geological data and maps are invaluable in establishing these conditions. In controlling such regions of high streambed infiltration, stream channel liners, wooden sluice boxes, and canals may be used. Regardless of the technique, the objective is to bridge the streamflow over or around the permeable zone to minimize groundwater recharge and flow from the stream.

Surface Flow Control

Various schemes have been adopted over the years to reduce surface water inflow to active mines and thereby improve working conditions and reduce pumping and treatment requirements. The initial objective is to divert as much surface water as possible from the disturbed area by means of diversion ditches and water flow channels that utilize the existing natural topography. On occasion, streams may have to be temporarily diverted with new channels or pipes.

The active area of disturbance should be kept minimal, and the period of time before reclamation and revegetation should be kept as short as possible. Working time should be coordinated with the local growing season as much as possible.

Highwall diversion ditches are used throughout the mining region to intercept sheet runoff and runoff in gullies and small streams. These structures are often left intact following mine restoration, hence they continue to divert excessive runoff from backfilled areas. Not uncommonly, however, diversion ditches may become silted with time, breached by erosion, or filled with ice packs in winter, thereby reducing their effectiveness. Rarely are provisions made to maintain these structures following backfilling. In addition, such ditches may be undersized and hence unable to handle longer-term siltation and erosion problems. On the other hand, ditch design to protect against the six-hour, 100-year flood may be excessive and may in fact cause more problems than it was intended to solve. Large diversion ditches can cause serious erosion situations and flooding problems.

Recently, more emphasis is being placed on erosion and sediment control in surface mining, and more conservative design and construction practices are being called for to minimize erosion and siltation during and following mining (see for example, Hittman Associates, 1976). Stone-riprap-lined diversion ditches and protected channels constructed across backfilled areas are now in use in some mining districts, as are concrete structures used to check flow velocities and half-round concrete, metal, and bituminous fiber pipes (Figures 13 and 14). Many innovations are possible for reducing sheet erosion and hence sedimentation derived from strip mines. However, conflicts will arise that must be considered in premining planning. Backfill slopes

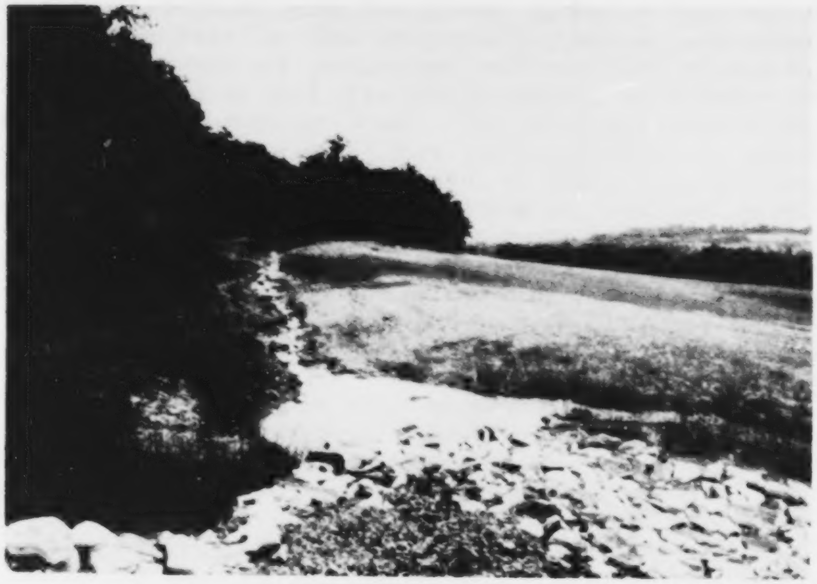


Figure 13. Use of riprap in waterways to dissipate flow energies and protect channels. Note highwall diversion ditch. (Kato region, Clearfield County, PA).

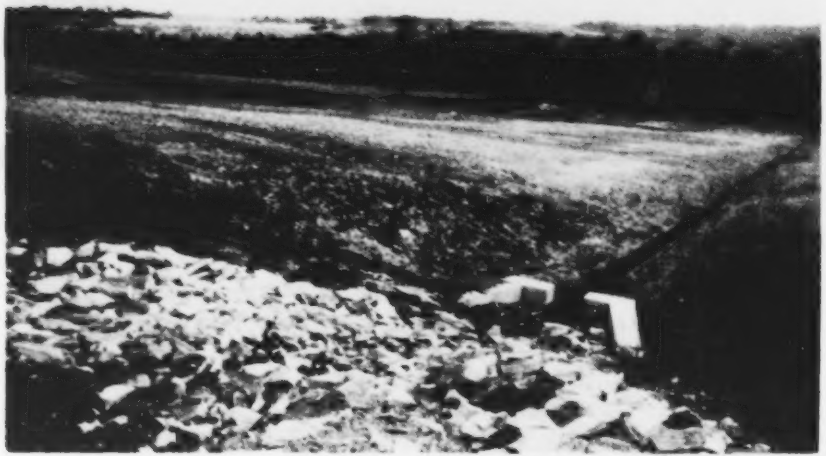


Figure 14. Use of riprap in waterways to dissipate flow energies and protect channels, and use of half-round metal pipes and concrete structures to divert surface runoff across surface mines. (Kato region, Clearfield County, PA).

may be designed to reduce runoff, and hence erosion and siltation (Figure 15). Any restoration design and structure that provides detention storage to surface runoff, shallow close depression, terraces, dikes, ditches, etc., or that reduces the surface slope, will tend to have a direct benefit in reducing erosion and siltation. Where the channels and/or beds of these structures are permeable, they will increase the infiltration and recharge rate and can be designed to intercept and recharge nearly all surface runoff. Such design can have the desirable effects of adding to groundwater recharge and storage, reducing flood peaks in nearby streams, and increasing baseflow of mine seeps and nearby springs and streams. Where acid-producing spoils are involved, however, this design may greatly enhance the volume and pollution load contained in mine drainage long after backfilling has been completed, and thus negative effects may result.

A range in possible problem types should be considered in mine planning. Flexibility should be allowed in selecting optimal restoration techniques. A technique designed to promote surface runoff and reduce infiltration and recharge, for example, may help to reduce chemical pollution problems associated with mining only to increase the suspended solids (sediment) problem. A combination of remedial measures can be adopted to address such conflicts. For example, structures can be provided to channel water across sloping backfill deposits to promote maximum runoff; at the same time, sediment basins, detention storage structures, etc. can be provided beyond or along the lower edge of the mine to control siltation. In fact, mine restoration can be accomplished in stages from the top of upland spoil regions to the base of the slope and/or near the coal crop. Sediment traps can be provided by leaving partly backfilled areas along the lower slope until upland surfaces are largely stabilized by vegetation. Two to three years may be required to establish a suitable sod. By this scheme, the lower slopes would be restored last to establish the final continuity of slope. Current mining practice in hilly regions, however, often requires that the lower outer slopes first disturbed by mining be backfilled following a routine schedule specified in mine permits and restored as mining progresses in the upslope direction. This approach promotes runoff, erosion, and siltation along lower restored slopes that cannot always be controlled by diversion ditches and small siltation basins. Commonly, no sediment control facilities are provided along the base of these slopes.

Some mining permits in more hilly mining regions require diversion ditches be placed below the coal crop to intercept surface runoff, sediment, and poor quality mine drainage that may flow through, above, or below a coal crop barrier (Figure 16). Many of the same problems must be considered when designing these structures as for highwall diversion ditches, with the added problem that sheet erosion from a single storm following backfilling can completely fill such a sediment trap or cause it to be breached. Under these circumstances, ditches will fail to intercept water and sediment intended to be conveyed to siltation basins or water treatment facilities.

The position of these diversion ditches with respect to the groundwater flow systems and stratigraphic sequences must also be considered on a mine-by-mine basis. A ditch located in a recharge area in a highly permeable bed rock and/or overburden soil deposits, for example, can leak and fail to

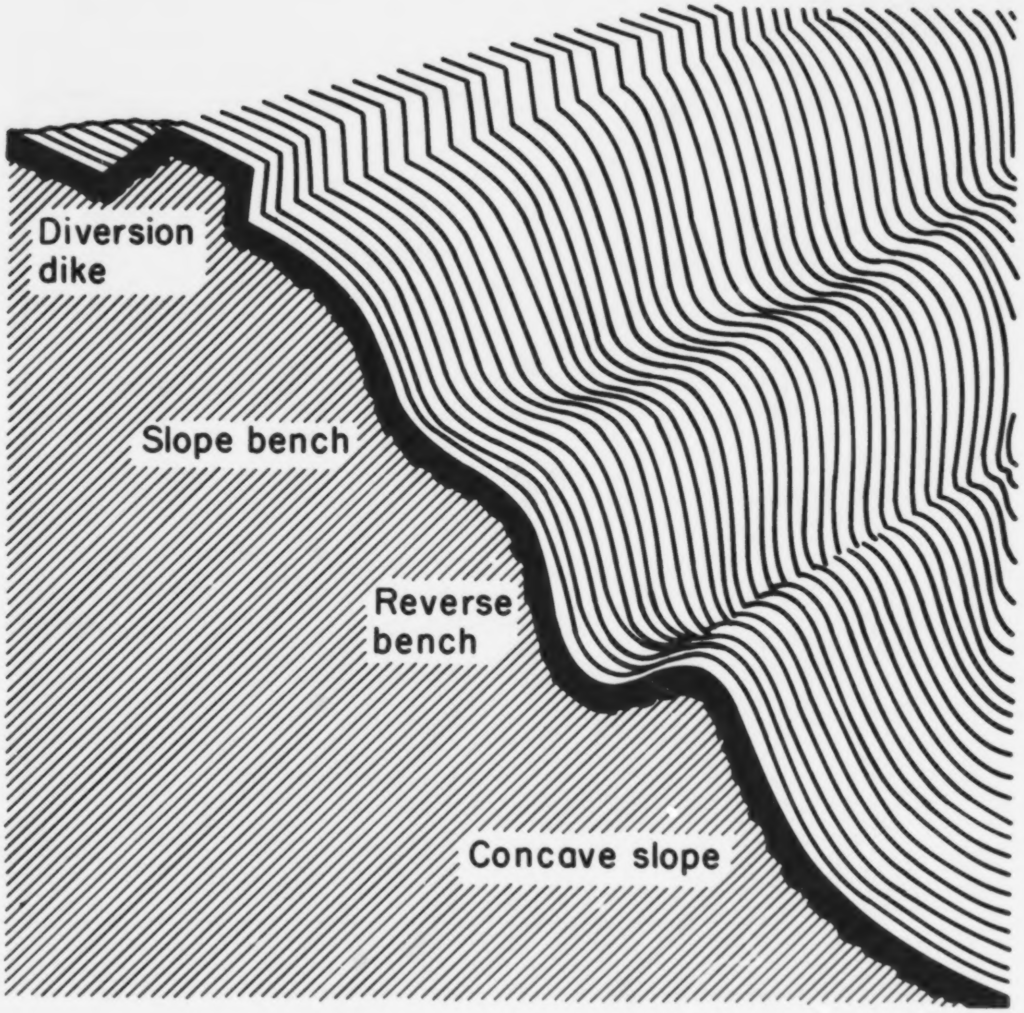

Diversion dike
Slope bench
Reverse bench
Concave slope

Figure 15. Slope reduction measures using sloped benches, reverse benches, and concave slopes (Hittman, 1976).

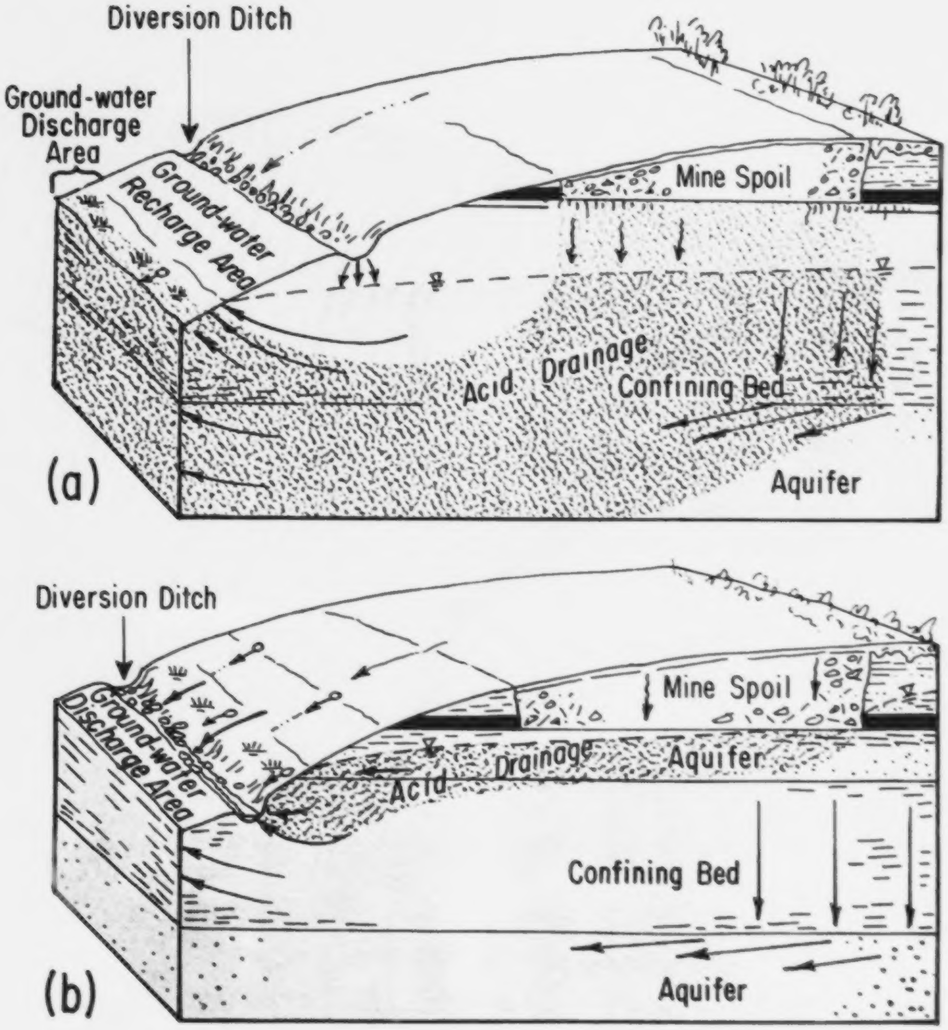

Diversion Ditch
Ground-water Discharge Area
Ground-water Recharge Area
Mine Spoil
Acid Drainage
Confining Bed
Aquifer
(a)
Diversion Ditch
Ground-water Discharge Area
Mine Spoil
Acid Drainage
Aquifer
Confining Bed
Aquifer
(b)

Figure 16. Diversion ditches placed below coal crop to control surface runoff, groundwater runoff, and siltation. (a) Ditch is in a groundwater recharge area and fails to collect polluted groundwater for downslope routing and treatment. (b) Ditch is in groundwater discharge area below the groundwater flow channels containing acidic drainage. Acidic drainage can be channeled to points of treatment and will protect downslope water supplies and water resources.

convey mine water to the intended point of treatment (Figure 16). Such a diversion structure may provide little if any protection to downslope land and water resources and to adjacent property owners. Pollutants contained within deeper groundwater flow systems and derived from nearby mines, for example, may bypass the diversion ditch entirely and be discharged to regional groundwater sinks or discharge areas located along master streams and tributaries at lower elevations.

Water directed around the disturbed area, water collected from the disturbed area, and water pumped from the open mine cut should be transferred by an adequate-sized pipe or stabilized channels to prevent additions of further sediment. These waters must be directed to settling ponds to prevent the discharge of unacceptably high suspended solids or turbidity. The use of flocculants may be essential to reducing sediment loads. If the quality of these collected waters does not meet effluent guidelines, it may have to be treated to achieve proper pH, alkalinity, manganese, and iron levels. It usually is desirable to treat waters of unacceptable chemical quality separately from waters with only a high sediment loading. Separate treatment will result in requirements for multiple treatment basins, but treatment will be more efficient and quantities of reagents may be decreased. Most commonly, poor quality water is related to open-pit locations.

Usually permanent or semipermanent settling basins can be established to receive all collected waters and to establish a common discharge point. These basins must be of adequate size and must provide for sediment removal as well as separation of floating debris. They must be located a sufficient distance from the receiving stream to preclude flooding during high water. The basins should be constructed with adequate stability and impervious bottoms. Usually, clay bottoms are adequate, although some situations may require the use of liners or chemical sealants (Figure 17). Liners pose problems during sediment removal operations.

Details of erosion and sediment control planning in surface mining have been developed elsewhere (Hittman Associates, 1976).

Control of Soil Water

Some surface mines in mining districts have been abandoned for two or more decades, and still spoil banks are only sparsely revegetated. No special attempt was made in early mining to replace topsoil or unconsolidated overburden deposits above bed rock spoil materials. Rather, these materials were often mixed with fragmented shale, siltstone, sandstone, and fireclay bed rock in a random manner. The percentage of fine-grained matrix material has increased over the years as shale, siltstone, and clay blocks have broken up by mechanical weathering; but the moisture-holding capacity of these deposits is still very low when compared to the original soil. Many spoil banks observed have a very high infiltration capacity, high porosity, and high coefficient of permeability compared with the original overburden spoil and bed rock disturbed by mining. All of the above factors favor the rapid infiltration of surface water, which maximizes mine drainage formation as it

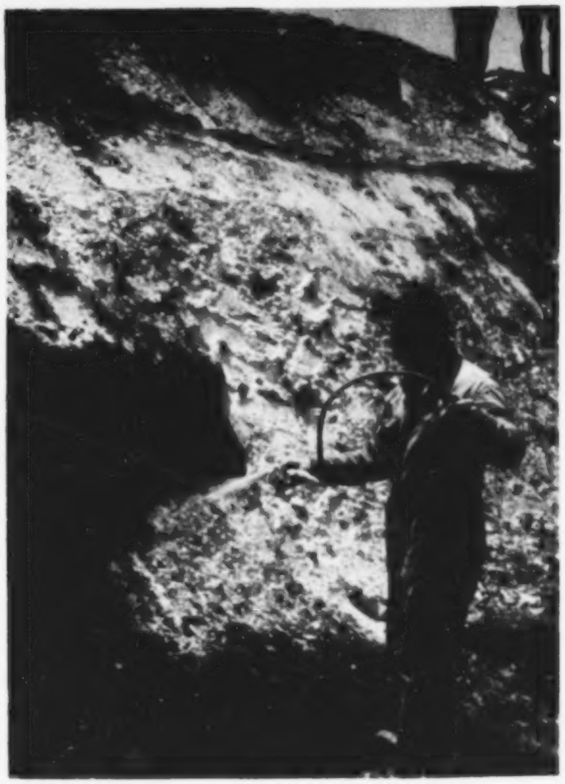


Figure 17. Spray application of chemical sealant on side/ bottom surfaces of a coal settling basin.

facilitates groundwater recharge. Backfill procedures that result in incomplete restoration produce closed surface depressions that also favor ponding areas and greatly increase infiltration to spoil banks (Figure 18).

A regrading program will help to eliminate depressions and ponding areas, and it could help to promote more runoff by overland flow, particularly along steeper slopes. However, the coarse-textured nature of most bed-rock-derived spoil deposits and their high permeability characteristics should favor rapid internal drainage and groundwater recharge for years to come until a less permeable surface soil is formed. Infiltration and recharge may be less where thicker glacial drift overburden sediments are placed above bed rock spoil deposits. However, even here, recharge can be greatly increased within hummocky spoil deposits over that of initial premining conditions.

The transpiration losses of soil moisture from sparsely vegetated, abandoned spoil banks will be far less than for the original vegetation cover.

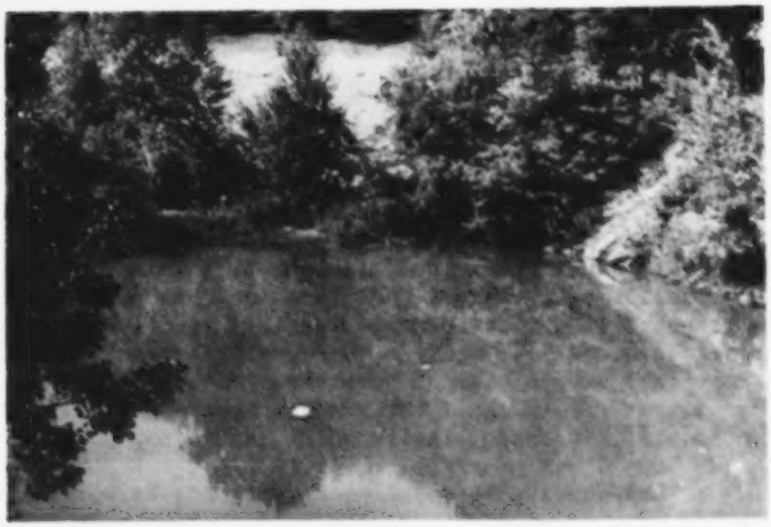


Figure 18. Ponding areas resulting from incompletely restored backfill procedures.

Evergreens and other trees that survived initial transplanting in acid spoil banks are still relatively small and widely scattered in many areas, despite their 10 to 30 years of age. Their root systems are restricted as well. Ground cover between trees is still essentially sparse to nonexistent in some strip mine areas lacking a soil cover. Poor survival of vegetation and slow adjustment to some mined areas most likely reflect the acid nature of the spoil banks and their poor moisture-holding capacity.

The evapotranspiration losses of soil moisture have not been measured or calculated for these bare spoil materials under the range of climatic conditions experienced in the eastern coal mine district; but values are expected to be very low, generally less than 12.7 to 24.4 cm (5 to 10 in.) per year. Interception and evaporation losses from vegetation is still trivial in most areas and will not increase until the area is revegetated on an extensive basis. Some spoil banks abandoned nearly 30 years ago show no transpiration losses of soil moisture. In time, however, evapotranspiration consumption of precipitation should begin to approach initial conditions as a lush vegetation cover is reestablished. The significance of reduced inflow of water and pollution reduction from mine spoil deposits has not been established in the literature adequately to make a firm statement about the total benefits that should be expected by restoration of vegetation. But reduced inflow of soil water to disturbed land should result in a reduced volume of mine drainage and, it is hoped, a reduced pollution load.

Soil moisture evapotranspiration losses have been measured near State College, Pennsylvania, and have been found to range from 63.5 to 71.12 cm (25 to 28 in.) of annual precipitation. Several hydrologic budget studies have been completed in central Illinois, and evapotranspiration losses were found to vary from year to year, as expected (Tables 6, 7, and 8). Illinois is a slightly warmer region with a lower annual precipitation than Pennsylvania and mixed woodland and farmland vegetation. Although it has not been established that a reduction in soil moisture (and hence in groundwater recharge) will result in a reduced pollution load from spoil banks, it is reasonable to expect that this will be the case. The shallow soil zone may also act as a partial oxygen sink or sump through the decay of organic matter and plant root respiration. It has not been shown that this oxygen uptake mechanism will, in fact, significantly reduce the oxidation rate.

Regrading of abandoned acid spoil banks will not be sufficient to establish a cover crop of trees or grasses unless other more costly steps are also taken. Namely, lime or limestone and fertilizer may be required to promote early and rapid growth. Municipal sewage sludges and effluents can also serve this same role. Benefits are derived from their water content, nutrient content, often favorable alkalinity, and the fact that they stimulate rapid plant growth.

Left to themselves, acid spoil banks may require 25 to 30 or more years before evapotranspiration losses increase to 10 to 15 in. (25 to 38 cm) per year. This goal could be achieved within a 2- to 3-year period with the use of fertilizer, lime or limestone, sewage effluents and sludges, and seeding of grass combined with trees. A topsoil dressing would only hasten the revegetation process. Ultimately, the evapotranspiration rate may be increased to 20 to

TABLE 6. MONTHLY AND ANNUAL EVAPOTRANSPIRATION IN INCHES OF WATER OVER HADLEY CREEK BASIN, 1956-58[*]

Month	1956			1957			1958		
	ET_s[†]	ET_g	ET	ET_s	ET_g	ET	ET_s	ET_g	ET
Jan.	---	---	---	---	neg.	---	---	neg.	---
Feb.	---	---	---	---	neg.	---	---	neg.	---
Mar.	---	---	---	---	neg.	---	---	neg.	---
Apr.	---	0.12	---	---	0.09	---	---	0.11	---
May	---	0.08	---	---	0.11	—	---	0.17	---
June	---	0.11	---	---	0.23	---	---	0.14	---
July	---	0.10	---	---	0.18	---	---	0.14	---
Aug.	---	0.08	---	---	0.12	---	---	0.33	---
Sept.	---	0.06	---	---	0.08	---	---	0.18	---
Oct.	---	0.03	---	---	0.07	---	---	---	---
Nov.	---	neg.[‡]	---	---	neg.	---	---	---	---
Dec.	---	neg.	---	---	neg.	---	---	---	---
Annual Total	---	---	---	23.80	0.08	24.68	---	---	---

[*] Source: Schicht and Walton, 1961.

[†] ET_s = soil water and surface water evapotranspiration

ET_g = groundwater evapotranspiration

ET = total evapotranspiration

[‡] Negligible.

TABLE 7. MONTHLY AND ANNUAL EVAPOTRANSPIRATION IN INCHES OF WATER OVER PANTHER CREEK BASIN, 1951-52, and 1956*

Month	1951			1952			1956		
	ET_s†	ET_g	ET	ET_s	ET_g	ET	ET_s	ET_g	ET
Jan.	---	neg.‡	---	---	neg.	---	---	neg.	---
Feb.	---	neg.	---	---	neg.	---	---	neg.	---
Mar.	---	neg.	---	---	neg.	---	---	neg.	---
Apr.	---	0.08	---	---	0.13	---	---	0.06	---
May	---	0.27	---	---	0.43	---	---	0.11	---
June	---	0.18	---	---	0.18	---	---	0.12	---
July	---	0.05	---	---	0.47	---	---	0.13	---
Aug.	---	0.34	---	---	0.33	---	---	0.14	---
Sept.	---	0.23	---	---	0.28	---	---	0.12	---
Oct.	---	0.04	---	---	0.19	---	---	0.06	---
Nov.	---	neg.	---	---	neg.	---	---	neg.	---
Dec.	---	neg.	---	---	neg.	---	---	neg.	---
Annual Total	23.52	1.19	24.71	21.93	2.01	23.94	18.01	0.74	18.75

*Source: Schicht and Walton, 1961.

†ET_s = soil water and surface water evapotranspiration

ET_g = groundwater evapotranspiration

ET = total evapotranspiration

‡Negligible.

TABLE 8. MONTHLY AND ANNUAL EVAPOTRANSPIRATION IN INCHES OF WATER OVER GOOSE CREEK BASIN, 1955-58*

Month	1955			1956			1957			1958		
	ET_s†	ET_g	ET	ET_s	ET_g	ET	ET_s	ET_g	ET	ET_s	ET_g	ET
Jan.	---	neg‡	---	---	neg.	---	---	neg.	---	---	neg.	---
Feb.	---	neg.	---	---	neg.	---	---	neg.	---	---	neg.	---
Mar.	---	neg.	---	---	0.26	---	---	neg.	---	---	0.30	---
Apr.	---	0.33	---	---	0.55	---	---	neg.	---	---	1.01	---
May	---	0.64	---	---	0.64	---	---	0.26	---	---	1.16	---
June	---	0.66	---	---	0.28	---	---	1.04	---	---	0.13	---
July	---	0.64	---	---	0.24	---	---	0.78	---	---	0.31	---
Aug.	---	0.28	---	---	0.13	---	---	0.62	---	---	0.66	---
Sept.	---	0.10	---	---	0.13	---	---	0.40	---	---	1.23	---
Oct.	---	0.01	---	---	0.03	---	---	0.10	---	---	---	---
Nov.	---	neg.	---	---	neg.	---	---	neg.	---	---	---	---
Dec.	---	neg.	---	---	neg.	---	---	neg.	---	---	---	---
Annual Total	23.10	2.66	25.76	22.09	2.26	24.35	21.10	3.20	24.30	---	---	---

*Source: Schicht and Walton, 1961.

†ET_s = soil water and surface water evapotranspiration

ET_g = groundwater evapotranspiration

ET = total evapotranspiration

‡Negligible.

25 in. (50.8 to 63.5 cm) of water per year (Ohio, Pennsylvania, West Virginia region), which should greatly reduce the pollution load derived from the region. The remaining pollution load following this revegetation effort may still greatly exceed the premining condition for many years to come. Other corrective action will have to be taken to bring about further pollution abatement.

Figure 19 is offered for planning purposes. It shows the potential evaporation of surface water from lakes across the United States, based on computed and measured amounts. The total potential evapotranspiration from surface, soil water and groundwater sources will differ from the figure shown. During some seasons of the year, soil moisture deficits may result that reduce actual evapotranspiration losses below the potential.

Strata Dewatering

Groundwater control for mine excavations may be accomplished either by dewatering the open pit after the water has come in contact with the highwall and mine spoil deposits, or by intercepting the water as groundwater within soil or rock below or adjacent to the mine. Dewatering in advance of inflow to the open pit has the advantage of eliminating the need to treat the water where acid reactions are inevitable and water quality standards must be met in the receiving body of water. For economic reasons, only the most important water-yielding deposits might be dewatered adjacent to the mine, as the objective is to reduce the inflow as much as possible, not to eliminate it entirely no matter what the cost.

Dewatering to prevent slope failures within unconsolidated overburden deposits may prove useful where mines are located close to highways, streams, lakes, buildings, etc. (Terzaghi and Peck, 1967; Coates and Yu, 1977). However, reductions in pore-water pressures are intended to increase the shearing resistance of the deposits, not necessarily to reduce water inflows and water treatment requirements significantly.

Important water-bearing deposits that will contribute significant volumes of water to mines should be delineated in advance, and their aquifer and confining bed properties should be determined by appropriate pumping test procedures. Water level fluctuations should be determined on a seasonal basis along with the proximity of the mine to streams, lakes, and marshes. Water level changes within surface water bodies also should be assessed. These water level changes may be entirely natural and not caused by mining, as often believed or claimed by adjacent landowners; rather they may be related to seasonal changes or droughts.

Dewatering for pollution control need not be as demanding as dewatering to aid foundation construction or to protect structures and slopes. Some pumping will always be required from open pits placed below the water table, but this can be relatively minor for mines located in poorly permeable strata. Uncontrolled surface runoff and direct precipitation also must be pumped on an intermittent basis. An assessment of flood potential would be

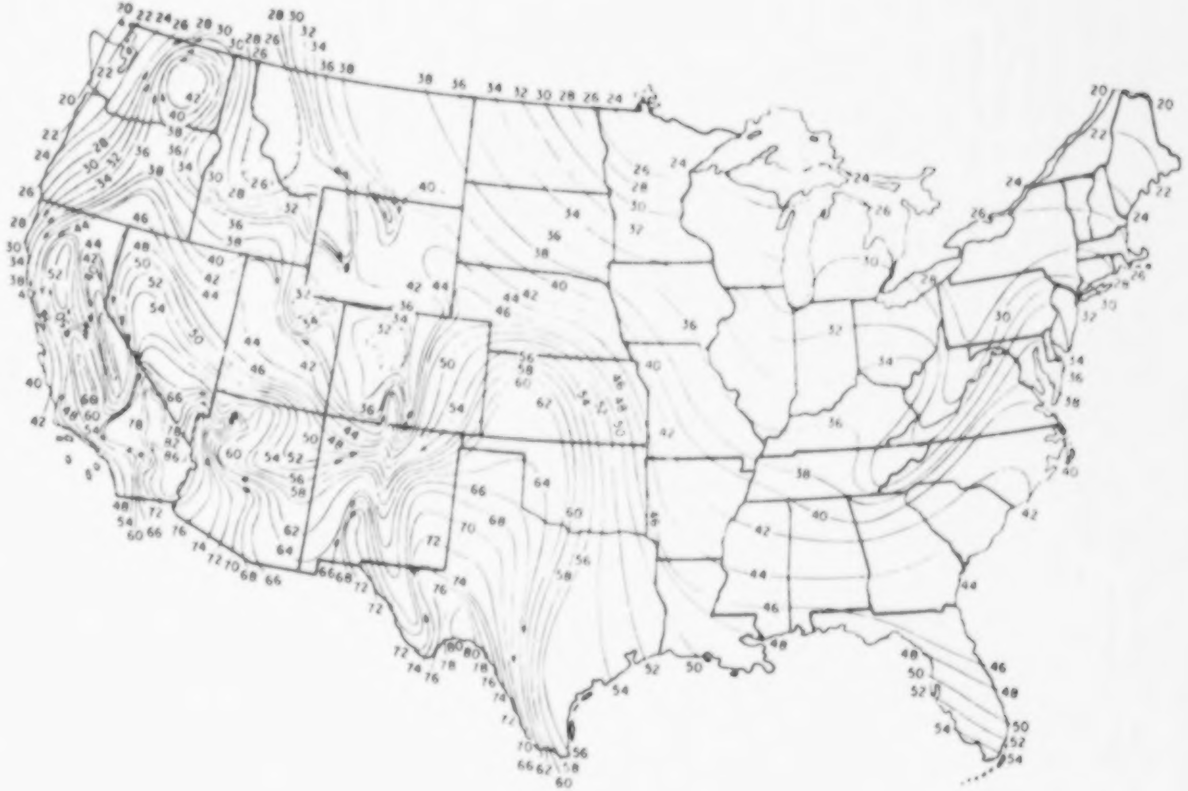


Figure 19. Average annual evaporation (inches) from shallow lakes (From U.S. National Weather Service).

appropriate where mines are to be placed on flood plains of streams and rivers. Flood protection embankments may be desirable when frequent floods are possible (see Volume 4, Mine Hydrology).

Any unexpected large increase in groundwater flows encountered during mining will go into temporary storage within the mine pit. Pumps can be added to control this water as needed. Provisions can be made to intercept this water within aquifers before it becomes polluted in the mine environment. However, some estimate will be required in advance to determine the number and spacing of wells that might be required to reduce groundwater inflow. This process will include determining the power requirement during the period of dewatering and selecting the number, spacing, diameter and depth of wells, casing and screen requirements, and pump size. The potential cost advantage of intercepting this water as groundwater compared with the cost of pumping and treating it as mine water should be determined. Published literature shows that a considerable range in treatment cost is possible, depending on water quality encountered and treatment requirements that must be met. Aquifer dewatering to control high quality water or to reduce turbidity within mine water may not be justified.

The rate of spread of cones of pumping depression is dictated by a number of variables, as discussed in Volume 4. These variables include items such as coefficient of storage and transmissivity of the aquifer, the aquifer thickness, width and length, the thickness and permeability of confining beds, the head differences between source beds and aquifers being dewatered, the pumping rate of individual wells, and the number and spacing of dewatering wells. The goal in aquifer dewatering is to reduce the potentiometric surface to or below the level of the mine floor within aquifers that underlie the mine where groundwater movement is upward, or to reduce the hydraulic gradient and saturated thickness within aquifers exposed along the highwall.

As an alternative, it may be desirable to control or maintain water levels within important aquifers adjacent to the mine that are being used for municipal, irrigation, or industrial purposes. Hydrogeological analyses similar to those mentioned above would be required if recharge wells were to be used to create cones of impressions (water level buildups) in the water table or potentiometric surface, or if sheet piles, grout curtains, or clay barriers were being considered to impede flow within the aquifer near the mine highwall (Figures 20 and 21). A line of recharge wells (Figure 20) can be used to maintain the water levels and yield of nearby production wells. This system can be used during mining. A clay cutoff barrier (Figure 20) can prevent excessive loss of groundwaters to the surface mine during and following mining. This system can be used to control groundwater flow and maintain heads during and following mining. Placement of the clay barrier against the aquifer exposed along the highwall (Figure 20) can prevent groundwater losses to highly permeable mine spoil deposits. Sheet piles and grout cutoff curtains (Figure 21) can be used in unconsolidated overburden deposits to maintain groundwater levels during and following mining. Thus a balance can be achieved between maximum coal extraction and conservation by preserving aquifers and protecting water supplies throughout the mining process.

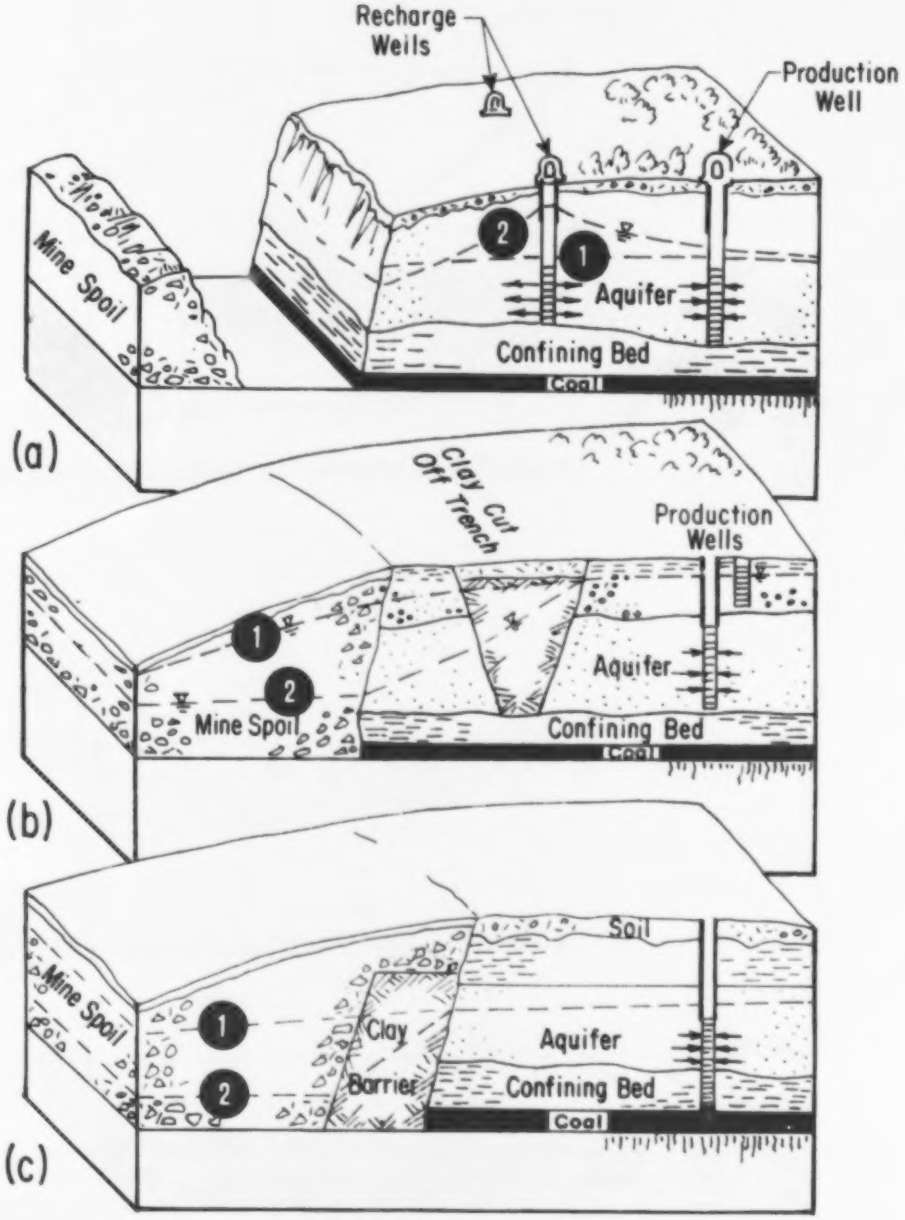

Recharge Wells
Production Well
Mine Spoil
2
1
Aquifer
Confining Bed
Coal
(a)
Clay Cut Off Trench
Production Wells
1
2
Mine Spoil
Aquifer
Confining Bed
Coal
(b)
Mine Spoil
Soil
1
2
Clay Barrier
Aquifer
Confining Bed
Coal
(c)

Figure 20. The use of recharge wells (a) and clay cutoff barriers (b and c) to control drawdown within aquifers adjacent to surface mines and to reduce inflow, pumpage, and treatment requirements. (Note that in c, the clay cutoff barrier is placed against the aquifer exposed along the highwall to prevent groundwater losses to highly permeable mine spoil deposits.)

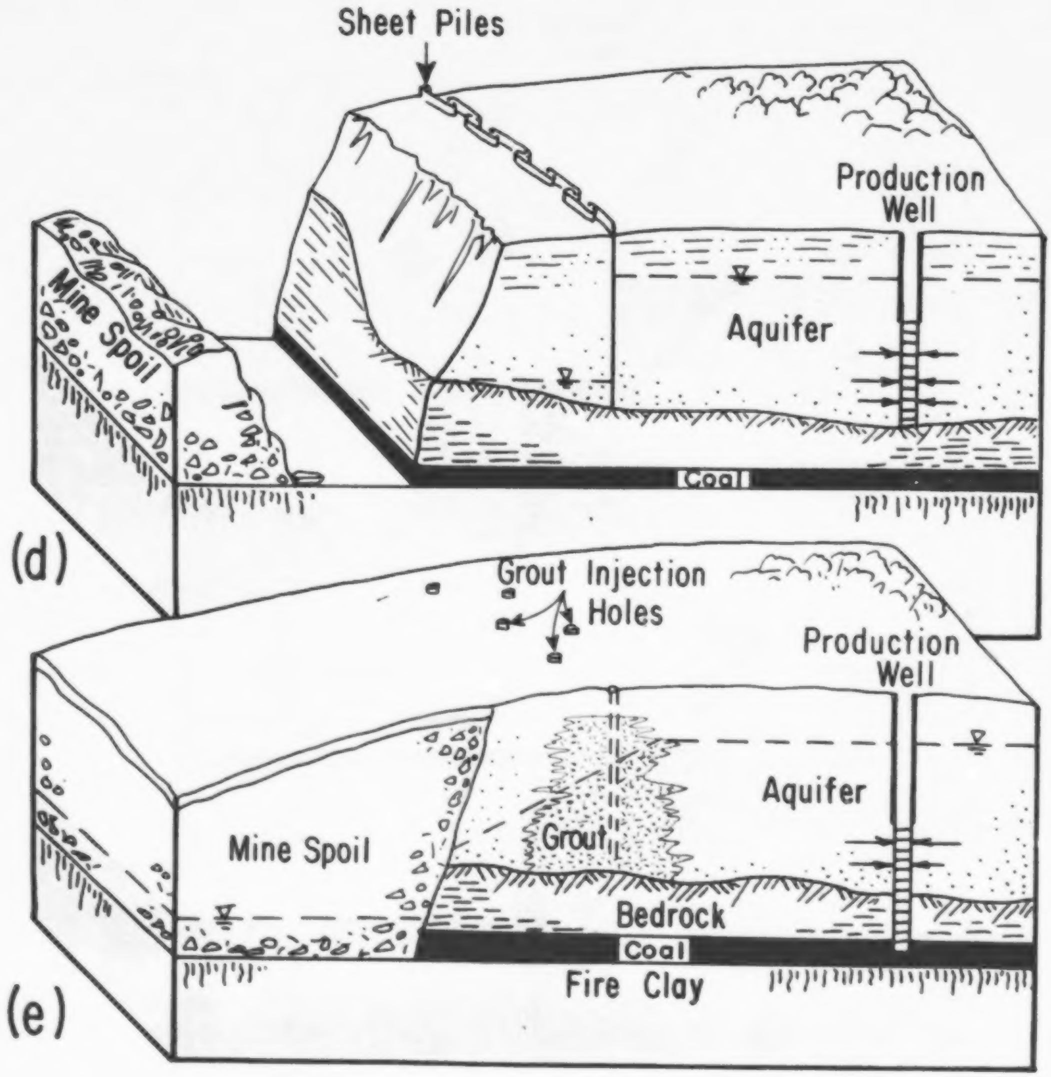

Sheet Piles
Production Well
Aquifer
Mine Spoil
Coal
(d)
Grout Injection Holes
Production Well
Aquifer
Mine Spoil
Grout
Bedrock
Coal
Fire Clay
(e)

Figure 21. Sheet piles (d) and grout cutoff curtains (e) used in unconsolidated overburden deposits to maintain groundwater levels during and following mining. (Note that sheet piles can be recovered from this situation, where groundwater levels will recover if backfilled with less permeable spoil deposits and hydraulic closure is insured for the mine spoil and aquifer.)

The magnitude of the dewatering project that would be required and length of time it must be continued vary greatly from project to project. depending on the rate at which water can be removed from storage within aquifers adjacent to the mine, the flow rate within these aquifers, and their recharge rates. These sources of water must be overcome or balanced out by dewatering wells.

Hydrogeological factors identical to those considered in routine groundwater resource evaluation work can be used for these evaluations. Where possible, hydrogeologic variables required in the analysis should be evaluated using field pumping test procedures that sample large masses of soil and rock rather than those that rely solely on laboratory tests conducted on cores and drilling cuttings. For example, both the radius of influence that a cone of pumping depression will spread to during a pumping test, and the volume of aquifer and confining bed material that is being evaluated by well hydraulics theory, have been demonstrated. The benefits of determining hydraulic properties in place on large sample sizes should be obvious when one compares the radius and volume of NX, BX, or AX cores typically subjected to laboratory analyses.

The concept of strata dewatering as a tool in water quality management is developed further in Section 5, Experimental Techniques for Treating Surface Mine Waters, which discusses the use of connector wells to control potable water and to dispose of polluted groundwater.

MINE DRAINAGE CONTROL ACTIONS BASED ON THE NATURE OF THE OVERBURDEN

In addition to minimizing the introduction of water into the mine area, the other pertinent factor in mine drainage control is the nature of the overburden strata and, in some settings, the strata under the coal. The important criteria are the presence of minerals that are water soluble and those that are convertible to a water soluble form by supplemental reactions. Of greatest concern is the pyrite content, the occurrence of calcareous strata, and strata permeability (previously discussed). The immediate concern is the establishment of the water pollution potential of the surrounding strata. Such evaluations are most complex, but they have been approached by a number of investigations (Emrich, 1966; Lovell et al., 1970).

Establishment of Water Pollution Potential

Evaluation of the water pollution potential of a stratum can be achieved by considering several groups of data:

- Detailed chemical and mineralogical data from the strata
- Physical data, especially on measurements of in situ strata porosity and permeability
- Chemical data on the quality of the waters found during core drilling and in surface runoff
- Data derived from direct laboratory and field simulations of strata capability to modify water quality.

Chemical and Mineralogical Evaluation of Strata for Water Quality Modification Potential--

Selection of strata for testing can probably best be made from drill samples, preferably cores that have not been comminuted. Each strata should be identified geologically and mineralogically, depths measured, and samples stored by chosen interval. Often the drill samples resulting from the exploratory program (designed for coal seam location and reserve evaluation) can be utilized. The number of cores selected is site specific, but care should be taken to include all strata from the surface to several feet below the lowest coal seam to be mined. Strata variations throughout the mine area should also be considered. The drill holes frequently provide a measure of water table levels, including potential capability of water sampling for analysis. The tests to be made on each strata section should include:

- Mineralogical identification with at least semiquantitative indication. Commonly this can be accomplished through manual examination by a skilled mineralogist, supplemented by microscopic and even x-ray diffraction analysis. Special attention should be given to identification of sulfide and carbonate (or other alkaline) minerals.
- Chemical analysis for total sulfur, carbonate, and acidity-alkalinity. In some situations, it may be helpful to perform a complete chemical inorganic analysis to establish compound format as limestone, dolomite, existing forms of sulfur (as sulfate, sulfide, and organic) and forms of iron (as sulfide, sulfate, carbonate, silicate, etc.). Some strata may show evidence of heavy metal mineralization, in which case semiquantitative spectrochemical analysis should be made for trace constituents such as manganese, zinc, cadmium, copper, nickel, etc. There may be regions and/or strata where evaluation for acute toxic substances at very low levels may require the use of atomic absorption, neutron activation, or microprobe procedures (as for arsenic, fluoride, beryllium, mercury, etc.).
- Special tests, such as the identification of pyrite in a given strata. It can be most helpful to carry out pyrite grain size and pyrite crystal format distributions (Caruccio, 1973). In these studies, it is helpful to relate pyrite occurrence to its mineral associations and apparent access to water and oxygen. There are no standard procedures for such studies, and they remain essentially research approaches. The techniques used for microscopic reflective petrographic measurements are usually applicable to pyrite (ASTM, 1974), while examinations of thin sections (Mansfield and Spackman, 1965) or the use of electron microscopy may be justified in some situations.

Establishment of Physical Data on Strata Porosity and Permeability--

Physical data on strata porosity and permeability must be combined with broader scale hydrologic and geologic data giving evidence of water table levels, strata permeability, and water flow potential in joints, fracture zones, and faults (Lovell and Gunnet, 1974, and Volume 4 of this series, Mine Hydrology).

Chemical Data on Natural Waters Associated with the Strata--

Samples of either groundwater or surface water, or both, taken from the area to be disturbed should be analyzed for temperature, pH, acidity, alkalinity, iron (ferrous, feric, total), aluminum, sulfate, manganese, carbonate, bicarbonate, hydroxyl, and conductivity, by means of accepted procedures (American Public Health Association, 1975). The presence of any acidic or sulfate component should be considered as a potential pollution source and should be correlated with its origin. The presence of acidity in a surface water sample should be further evaluated to establish whether the component could be associated with carbonic acid or with natural organic acids that would have no bearing on water quality degradation from mining causes. The presence of alkaline components would indicate a resistance to pyrite oxidation, the existence of alkalinity, and a potential buffering capacity. The conductivity level can be interpreted as an indication of total dissolved solids, and as a lixiviant factor for percolating waters.

Data Derived from Direct Laboratory and Field Simulations of Strata Capability to Modify Water Quality--

Despite various attempts to provide direct laboratory and field data for measurement of water quality degradation potential by various coal-related strata, the extensive number of variables, and especially the time factor, have not led to any generally accepted procedure. The most conspicuous procedures have been published by the Commonwealth of Pennsylvania (Emrich, 1966) to provide a basis for estimating quality and quantity of coal mine drainage for permit application.

Procedures developed by Braley (1949, 1960) and varied by Hall (1963) are typical. They involve leaching the sample with distilled water for 24 h to a few months. The tests are of limited significance because (1) the introduction of oxygen to the reaction sites is minimal, and (2) the tests do not incorporate many field conditions that are found to enhance the solubility of pyrite.

Another attempt to simulate the pollution potential of the strata was proposed by Goodwin and Emrich (Emrich, 1965, 1966) utilizing a modified soxhlet extraction that permitted the introduction of air into the distilled water contacting the sample.

Lovell et al. (1970) have proposed that these types of evaluations are of limited value because they are unable to relate, maintain, and correlate the multifarious variables that affect the oxidation of pyrite-coal materials and bring about their solution. They suggest that any test of the water pollution potential of coal strata must be backed by detailed mineralogical and geological data of the samples. Furthermore, any such test must involve two aspects; (1) the existence in the strata of water soluble materials at the time of sampling and analysis, and (2) a measure of the oxidation rate of sulfide minerals in situ and under active mining conditions.

The presence of naturally occurring soluble components would represent a composite status of material that has oxidized or has by nature a composition that results in acidic or alkaline waters. Thus a simple leaching test with distilled water that shows alkalinity or slight acidity would imply that with in situ conditions over recent geologic time: (1) there is little or no acidic material present in the strata, (2) if any pyritic material is present there has been little tendency to oxidize, or (3) there is a basic alkalinity in the strata that has neutralized any existing oxidation products. These data must be confirmed by detailed strata study, as previously described.

In an effort to make such a test as intensive as possible, a representative sample of the concerned strata is air dried and crushed to minus 60 mesh or finer. One gram of this sample is mixed with 200 ml freshly boiled, deionized, distilled water at room termperature for 24 h. The leach mixture is filtered and the filtrate analyzed for pH, acidity, alkalinity, iron (ferrous and ferric), sulfate, and conductivity.

A finely ground sample must be used to provide the greatest opportunity for all soluble material to dissolve. The use of larger particle sizes, as proposed by others, is biased by making only the limited surface area of a larger-sized particle available for solution, which will tend to ignore the overall composition of the strata. The excessive ratio of water to strata is desirable for achieving the greatest solubility of sparingly soluble components. The use of specially prepared leaching water is essential to avoid bias that may develop from the presence of carbonic acid or other trace components in other types of test waters that could enter the system from the laboratory air environment. A blank sample of the leach water should be maintained in the same environment as that during the test, since water of this quality will absorb carbon dioxide and other acidic gases common to the laboratory rapidly and give incorrect responses.

The second factor that must be involved in any test of coal strata pollution potential is some measure of the rate of oxidation of the in situ components within the test sample. Lovell did preliminary studies of such an approach, although the results are not published and should be extended. The test procedure devised sought to establish those conditions that would provide maximum and rapid oxidation and solubilization of any pyrite contained in the test sample.

The test stratum was crushed to minus 1/4 in. top size and supported in a glass column. The sample was subject to a continuous spray of the test lixiviant at a constant rate selected to achieve a constant wetted surface of all the test particles without column flooding for 24 h. The support column was left open for free contact to the atmosphere. The system effluent was collected and sampled at hourly intervals. The leachate was analyzed for pH, acidity, alkalinity, iron (ferrous and ferric), sulfate, conductivity, aluminum, calcium, and manganese.

The test lixiviant contained a known standardized synthetic mixture of ferrous and ferric sulfates to maintain a pH of about 3.0. It also included a known culture of *Thiobacillus ferrooxidans*, whose cell count was established. Such a solution is a strong lixiviant for pyrite. The final test data were evaluated to establish a maximum rate of pyrite solubility and correlated with known data of the test specimens such as pyrite content, particle size, and format.

Another approach, based solely on knowledge of the pyrite content of a strata sample, is suggested by Smith et al. (1974) and relates closely to standard soil analysis and classification procedures. This procedure measures the maximum amount of acidity that might be produced from a coal stratum by pyrite oxidation without regard to associated environmental effects. The importance of these effects was discussed in previous sections.

Drainage Control Approaches Using Overburden Segregation

Overburden may include three types of materials: (1) topsoil and materials conducive to plant growth, (2) clean, nonpolluting material, and (3) known pollution-forming material. Segregation of these three overburden materials allows for the most effective planning to prevent long-range pollution and to foster rapid formation of permanent vegetative cover.

Although the location for temporary storage of overburden is basically determined by economics and by the mining system, care must be given to pile stability as related to erosion, precipitation, absorption, and overburden solubilization. When timing and climate make it feasible, a temporary vegetative cover of the overburden is highly desirable. Surface drainage from such piles must be collected for treatment and sediment removal--especially materials that have high pollution-forming potential. In addition to vegetation of the overburden, other techniques to control runoff include the use of impervious barriers on or around the waste material. Such barriers may include clay, concrete, asphalt, latex (Tolsman and Johnson, 1973), plastics, or the so-called carbonate bonding (Skelly and Loy, 1973). Asphalt and concrete are costly. Rubber and plastic are often expensive, fragile, and generally less than satisfactory. The use of underdrains reduces the path of percolating water and leads it from the overburden. The protective procedures are most commonly applied to stored topsoil and to high pyrite-containing material rather than to the gross bulk of the overburden. The most effective preventive control of water quality degradation involves the rapid replacement and compaction of overburden combined with the construction of diversion ditches to channel surface runoff.

Recently, several manufacturers have made available synthetic polymer, small-mesh fabrics that can be used in haulroads and drainage construction to distribute loading, increase stability, and prevent reduction of designed channel water flows. The potential uses of this material in surface mining need further evaluation, particularly under field conditions.

Other considerations of overburden storage involve geographical trouble spots that should be avoided or that involve development of special measures. Examples are groundwater discharge or recharge areas and locations that are close to steep slopes.

Topsoils should be segregated and stored at a control location that will minimize transportation distances for storage and final distribution. They should be stored to minimize erosion and yet to provide adequate accessibility. In some regions, inadequate topsoil is available, and additional materials must be secured (occasionally from long distances at substantial costs). Various types of waste byproducts have been helpfully added to stored topsoils to increase fertility. Among such substances are sewage sludge, agricultural wastes from food processing, millorginite, fly ash, and bag house lime. The presence of toxic components in these additives must be considered.

As previously discussed, the vegetative cover also serves to control levels of runoff, percolation, and erosion. In the replacement of these materials, a knowledge of the groundwater levels and directions of flow that can be anticipated after reclamation is especially helpful. Compaction is essential during backfilling and can be very effective in minimizing percolation and groundwater recharge. Soft clays are most effective and usually available, although in some regions they may have to be transported some distance to the mine site.

After initial cuts while opening a surface mine, the clean overburden is preferably placed directly by the dragline, front-end loader, or by truck haul to final backfill locations. This pattern prevents multihandling associated with intermediate storage and allows immediate layering and compaction. Such procedures minimize the development of sedimentation and contact with water. In some surface mining systems, it may be necessary to separate large boulders (two ft or more) for placement over or in water courses to prevent erosion. The use of such boulders are helpful in the toe or head of hollow fills (see Figure 1).

The segregation of material with high acid-producing potential, the selective placement of it in non-water-flow areas, and controlled compaction can help to minimize water degradation. The use of clay or other impervious barrier covers on top of degrading material during backfilling will limit the amount of water contacting the material. Opinions vary regarding final placement of these materials: Some require placement along an unbroken low-wall barrier, while others prefer that it be placed along a final highwall. Under any circumstances, the material should be placed at locations that will minimize potential contact with groundwater. Recommended, but not actual practice, is to layer such toxic material with a base (such as limestone, hydrated lime, or bag house lime) during compaction to minimize potential pyrite oxidation. Toxic strata segregation is required in Pennsylvania and practised in other regions (southwest Missouri, for example). This same procedure can also be applied in developing refuse disposal areas. Toxic material should be covered by a layer of limestone aggregate to avoid armoring of limestone fragments with iron precipitates and thereby rendering them inactive for neutralization.

Minimizing Oxidation Conditions

Oxygen (from air) and oxidizing bacteria play a critical role in oxidizing pyrite to water soluble compounds that change water quality. All water quality control planning during surface mining should center on minimizing the introduction of oxygen into potential contacting waters and in minimizing favorable conditions for chemical pyrite oxidation and autotrophic bacteria growth. There are some unusual situations in which deliberate growth of these bacteria is sought to encourage oxidation and hydrolysis of water soluble ferric iron.

Recommended techniques for avoiding introduction of oxygen include:

1. Avoid water movement that will cause turbulence or splashing.
2. Minimize contact between water/air interfaces.
3. Design strip pits so that water will flow to a collection sump to permit its controlled removal from the active mining area. This may involve the following procedures:
    a. Elevation control
    b. Development of ditches or water flow channels (these may be unacceptably costly to develop)
    c. Development of channels near the highwall (since water most commonly originates from the highwall)
    d. Avoid sump collection areas that are traversed by moving equipment or that require mine water to percolate through mine spoil deposits
    e. Minimize the size and number of water collection sumps
    f. Keep collection sumps drained continuously -- do not allow working pit to collect large volumes of water.

Often, the underground water entering a strip pit via the highwall is of acceptable quality but is subsequently degraded by further contact with pyrite. It is generally advisable to introduce lime (hydrated or bag house) into the pit sump to keep these waters highly alkaline. Such procedures definitely inhibit pyrite oxidation and are especially helpful in warm weather, when the high alkaline conditions tend to limit the metabolic processes of autotrophic bacteria.

Limestone Treatment of Strip Mine Spoil

Background--

Alkalinity can be added to the system in advance of acid formation to provide a long-term, if not permanent, solution to the pollution problem derived from strip mine spoils. Limestone quarry waste can be used because it has a wide range of grain sizes that will insure a large surface area for reaction. The coarser-grain sizes should be retained near the land surface to provide a prolonged source of calcite to acid-forming reaction sites. Quarry waste frequently is less expensive than coarse-grained, screened stone, and it constitutes a little used byproduct of quarry operations. Most plants that operate lime kilns also produce significant volumes of stack dust, particularly where air pollution facilities have been provided. Bag house dust or flue dust may contain 40 to 60 percent active lime; the remainder is limestone in the fine-grained size.

Parizek and Tarr (1972) and Parizek (1973) explain that limestone should have many beneficial effects when applied as a top dressing to reclaimed mine spoil:

1. Limestone should help to neutralize acid water being produced onsite and precipitate iron and other mineral matter within the spoil banks, thus eliminating "yellowboy" and other precipitates before they reach surface water bodies.

2. Soil water should be buffered when exposed to limestone. This should increase the alkalinity of soil and groundwater and retard or even eventually eliminate the acid-forming reactions by retarding the growth of *Thiobacillus ferrooxidans*, *Ferrobacillus ferrooxidans*, *Thiobacillus thiooxidans*, and other catalytic iron-reducing bacteria.
3. The increased soil pH should favor the rapid regrowth of vegetation, particularly if fertilizer is added at the time the area is reseeded.
4. The increased plant growth in time (2 to 3 years) should greatly increase CO_2 production resulting from plant root respiration and decaying organic matter derived from annual "dieback" or organic litter.
5. The increased CO_2 pressure developed within the organically enriched soil zone will significantly increase the alkalinity derived from limestone when compared to the alkalinity produced from bare limestone aggregate exposed to rainfall. The buffer capacity of this soil water should be increased by nearly three orders of magnitude, which should be of consequence in abating acid mine drainage or retarding acid-forming reactions.

Significant results have been documented at a demonstration site under study in central Pennsylvania (Waddell, et al., 1979; Waddell, 1978). The long-term benefits of applying a limestone dressing to thick, highly acid-producing strip mine spoil still have not been adequately researched and documented, but the study by Waddell et al. (1979) is highly encouraging.

The neutralization process should reach a maximum within a few years after a lush growth of vegetation is established. This may be achieved in several ways. Both trees and grasses should be used to establish a dense and continuous ground cover. Moisture and fertilizer will be required to promote optimum growth. Both are contained in sewage sludge, which is available from many communities adjacent to strip mine areas. Liquid sludge can be sprayed from a central holding pond (temporary plastic-lined basin) on one or more occasions. A single 2-in (5 cm) application early in the growing season will be beneficial, but several other applications the same season will speed the growth process significantly and insure a high degree of survival during succeeding years. Water contained in the sludge also will aid germination and early growth. Less accessible areas on steep slopes, etc. also can be treated using a spray irrigation application method.

Solid sludge may be used as a substitute, but it will have to be spread by other means, and it may not be as easy to apply to steeper slopes. Dry sludge costs more, since sewage treatment plant operators are apt to want to recover dewatering costs by charging for the sludge.

Sewage sludges are superior to commercial fertilizers in that they are readily available, their disposal constitutes a second environmental problem, they will greatly aid in mine drainage abatement projects, and they should be cheaper than commercial fertilizers. Unfortunately, sludge may not always be available in large enough volumes close to every strip mine.

Limestone quarry waste is preferable to lime because it is cheaper, available at many limestone quarries, frequently has few other uses, tends to accumulate at quarry sites, is coarser-grained than lime, and should remain in soils for many years to come. Agricultural lime, on the other hand, will be consumed in time and can filter into coarse-grained, highly porous spoil banks and be lost to the neutralization reaction. Lime and limestone stack dust or bag house dust may be considered along with quarry waste where available.

Field Studies--

A demonstration study funded by the Federal Highway Administration to evaluate the full benefits of this restoration and abatement procedure was recently completed in Pennsylvania (Parizek, 1971; Waddell, 1978; Waddell et al., 1979). The limestone surface application method of abating acid drainage was investigated for spoil and embankment deposits disturbed by construction of Interstate 80 across part of the Allegheny Front in Centre County, Pennsylvania. This highway required extensive cut-and-fill operations through pyrite-bearing strata of Mississippian Age and coal- and pyrite-bearing strata of Pennsylvanian Age to the west. These cuts and fills resulted in the production of acidic drainage and pollution problems in springs and Jonathan Run, a small tributary stream crossed by the interstate highway. Officials of the Pennsylvania Department of Transportation (Penn DOT) and Federal Highway Administration (FHA) realized that this situation could occur throughout much of western Pennsylvania and other States. Hence they supported the demonstration study in hopes that the techniques involved might prove useful for reducing or eliminating the production of acidic drainage at the demonstration site and elsewhere. A proposal to demonstrate the utility of this important abatement procedure on strip mine spoil had been turned down previously by State and Federal pollution control agencies and was long overdue for field evaluation and documentation.

Acid reactions were shown to result within highway embankment valley fill deposits 20 to 60 m (66 to 197 ft) and approximately 150 m (492 ft) wide. Excavation waste dumps resulting from extensive highway cuts were also disposed of in the valley of Jonathan Run. These ranged from 10 to 15 m (32 to 49 ft) high and 30 to 90 m (98 to 295 ft) wide. Other regions of the valley were filled with 3 m (10 ft) of spoil and used for equipment storage, repairs, etc. during construction. Following construction, water quality changes were noted in springs draining into Jonathan Run and in a downstream recreation lake. Springs whose watersheds were located above the highway-derived spoil deposits remained good in quality except where influenced by a nearby coal storage yard.

The demonstration called for both a control site and treatment site so that the benefits of the treatment could be isolated from seasonal changes in water quality. Flow systems involved were rather complex and involved surface water that infiltrated the highway spoil, groundwater that was recharged below and adjacent to the spoil, some of the same groundwater that was discharged into springs and Jonathan Run, which flowed over and through spoil deposits.

Water samples were taken for a year before treatment and following application of limestone, limeplant flue dust, fertilizer, seed, saw dust and straw mulch in May 1974. Poor plant survival required reseeding followed by 6 months of additional monitoring with a vigorous grass cover. The sampling program terminated on December 30, 1977, or 2 years and 7 months later.

The study concluded that the fluxes of acidity and sulfate, and thus the production of acid at the treatment site, decreased by a factor of four after the treatment was applied (see Figures 22 through 26). The flux of sulfate at the treatment site has not been above 25,000 kg/day since November 1974, when the pH reached about 5.5 (See Figure 26). The pH has not increased above this level, except for random variation around the mean, since that time (Figure 22).

The pH may be controlled by two counteracting reactions. One is the neutralization of acid by water that has passed through the treatment layer. The other is the production of acid, with the reaction rate controlled by the abiotic oxidation of ferrous iron. As water of pH 6.0 or higher entered the fill material from the treatment material, the rapid, abiotic production of acid lowered the pH, resulting in lower reaction rates as the pH decreased. Eventually the pH will be low enough that, if bacterial catalysis has not become important, the production of acid will be too slow to exhaust the buffer capacity of the waters unless the residence time of bicarbonate-enriched soil and groundwater is very long. The maintenance of the pH at 5.5 at the site since January 1975 suggests that the pH at which bacterial catalysis becomes important was somewhere below 5.5. Except for one measurement, the lowest pH measured at the site since January 1974 has been about 5.2. The low pH measured could be in error, or it could indicate that the pH dropped below the point at which bacterial catalysis becomes important. If this second possibility were the case, the sample should have contained higher concentrations of sulfate than samples with pH greater than 5.2. But this was not the case. It appears that the pH at which bacterial catalysis becomes important is below 5.2. At pH 5.2, the oxidation rate is too slow to produce enough acid to deplete the buffer capacity of the water during the time the water remains in the fill material (Waddell, et al., 1979).

The authors of the report concluded that because of the similarity between the hydrologic and chemical settings in the study area and in many strip mines, this abatement technique has very good potential for reducing the production of acid from both active and abandoned strip mines, or anywhere that pyrite-bearing strata are disturbed. Its use is especially promising where earthmoving equipment is already available at the site and where sources of waste limeplant flue dust and limestone fragments can be found nearby.

UTILIZATION OF SETTLING PONDS

Overview

The development of sediment (fine soil particles) and its release from the surface mine site have great potential for stream degradation and must be controlled during clearing and grubbing from roadways, spoil piles, and active mine areas, and during reclamation. During clearing and grubbing the

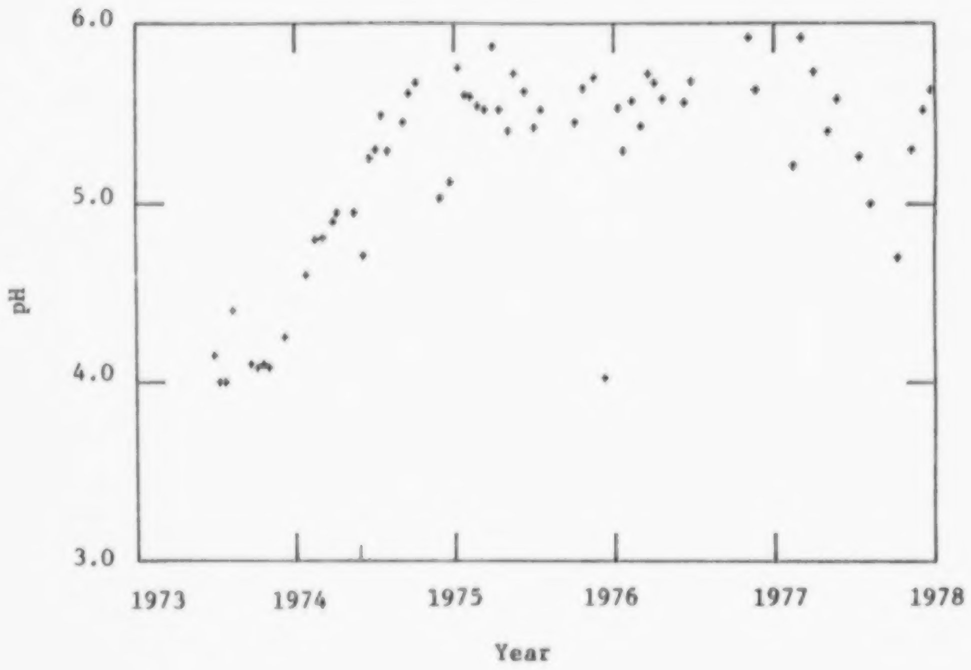


Figure 22. Plot of pH through time for the treatment site (Waddell, et al., 1979).

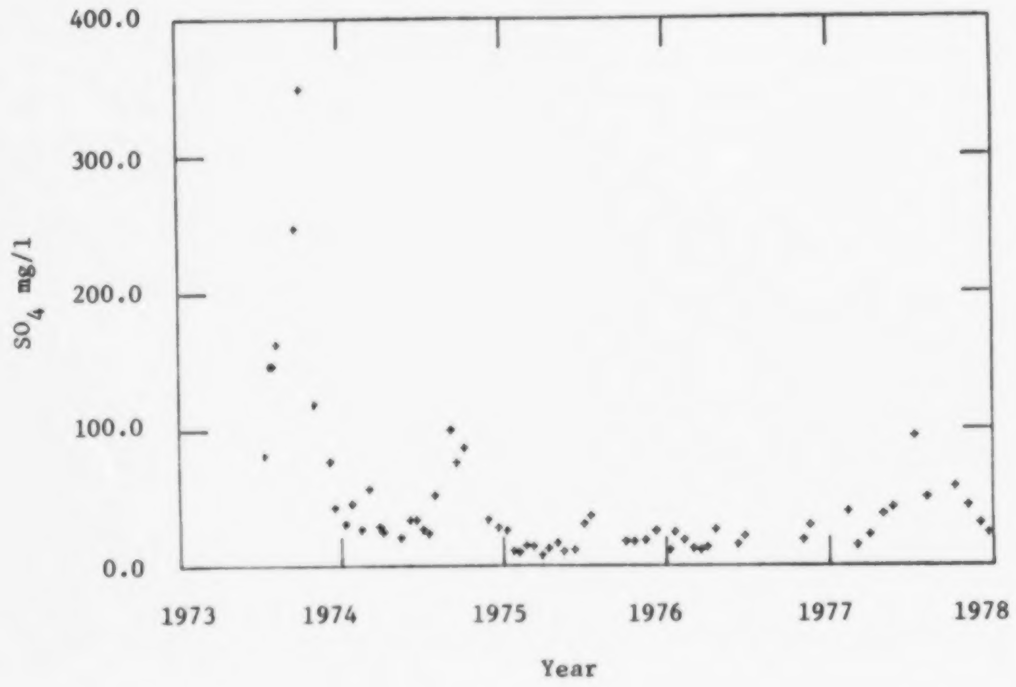


Figure 23. Plot of sulfate concentration through time for the treatment site (Waddell, et al., 1979).

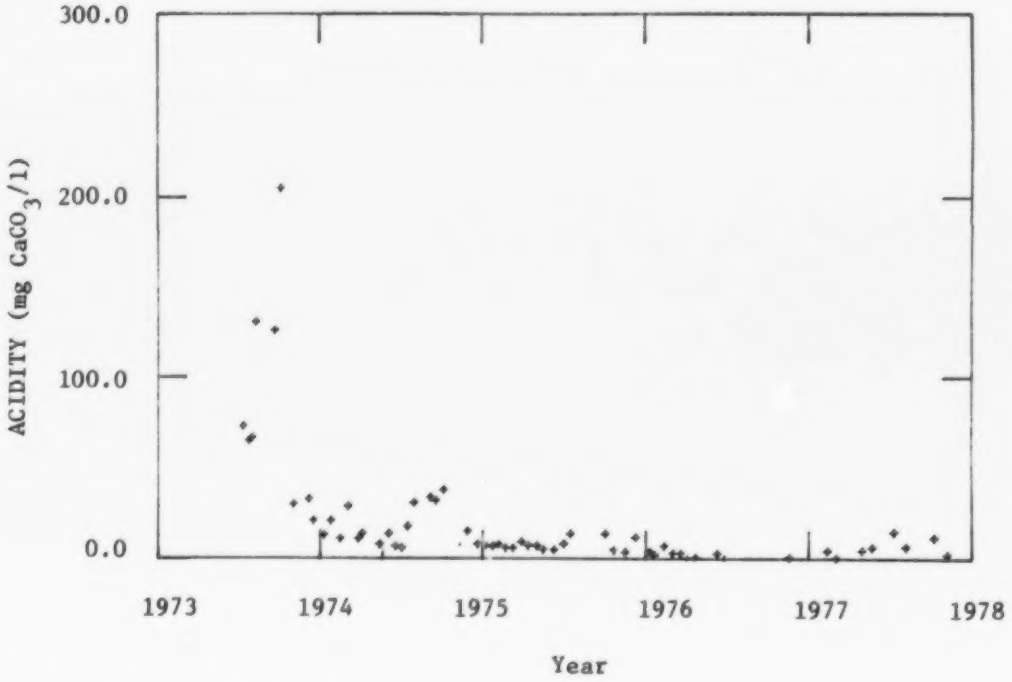


Figure 24. Plot of acidity through time for the treatment site (Waddell, et al., 1979).

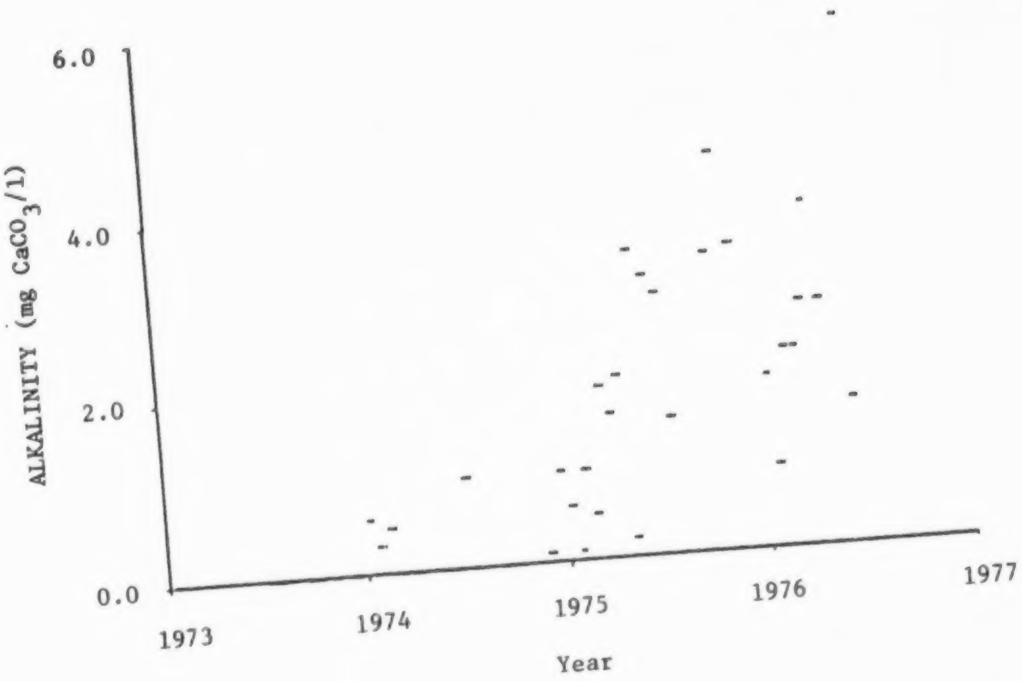


Figure 25. Plot of alkalinity through time for the treatment site (Waddell, et al., 1979).

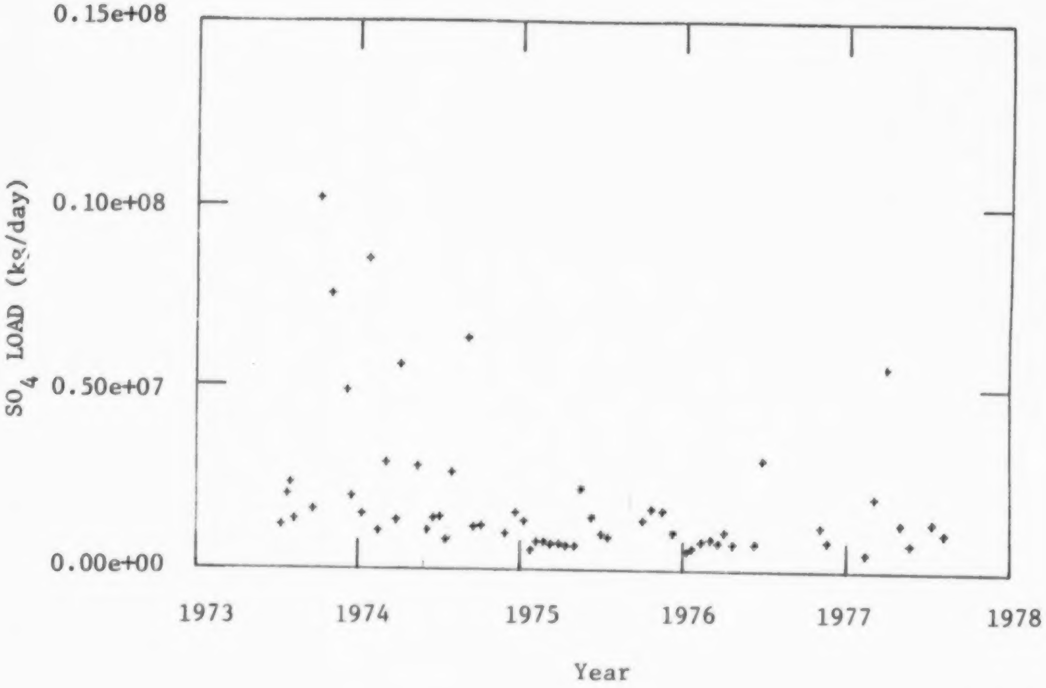


Figure 26. Plot of sulfate load through time for the treatment site (Waddell, et al., 1979).

concerns are area perimeter control, erosion on steep slopes, minimization of the time soil is exposed, improper soil overburden storage, and the reduction of soil infiltration rates. Roadways contribute to sediment through poor location, improper construction (including drainage structures such as paved chutes), inadequate maintenance, lack of cut stabilization, and improper safety berms. During overburden storage and active mining, the parameters include drainage access to the streams, distance to the stream, and development of fills. Reclamation requires proper grading and stabilization, reestablishment of drainways and aquifers, and structural stability.

The implementation of sediment control procedures must include engineering for the specific site, keeping disturbed areas small and exposed for a minimal time, and application of appropriate soil erosion and sediment control techniques. Sediment must be kept within the mining site. The control factors include water flow characteristics (velocity and turbulence) and particle characteristics (size, shape and density). Control techniques include vegetative buffers, sediment traps, sediment basins, and the use of coagulants (metal salts, metal hydroxides, and synthetic polymers). Though these systems control suspended particles, they also tend to provide additional opportunity to introduce dissolved solids to the water system, causing degradation in water quality.

To prevent the development of erosion channels during initial vegetative growth and to achieve stable slopes and drainage ways, some planning (usually involving mulches) is necessary. The initial use of grasses and legumes is favored because of the more rapid cover development, but trees may be planted subsequently if desired. Frequent monitoring of revegetated areas may be necessary for months to observe any development of erosion or water seepage. Should these conditions develop, followup corrective action may be necessary. There are many interrelated aspects that must be optimized to achieve an acceptable result. The development of seepage months after backfilling frequently poses the most difficult problems and may even require extended water treatment.

Transportation of Water from the Active Mining Pit to the Settling Pond

The generally preferred technique is to maintain water from an active pit under positive control by pumping rather than by gravity flow. To flow by gravity, the low wall, which serves as a barrier, must be broken. In some States (Pennsylvania for example) the low-wall barrier must remain intact to meet regulations, and thus water must be pumped. This is not a consistent requirement, nor is it fully accepted. Some mine operators object to the substantial loss of coal remaining in the low-wall barrier. However, frequently such deposits are highly oxidized and the coal is of inferior quality. Such coal barriers may tend to be water permeable unless deliberately sealed internally with clay. But, highly compactable and poorly permeable clay may not be readily available in the region. In the case of mountain top removal system, the Federal law requires that an outcrop barrier of sufficient width, consisting of the toe of the lowest coal seam, and its associated overburden are retained to prevent slides and erosion. However, the regulatory authority may permit an exemption to the retention of the coal barrier requirement under certain conditions (P.L. 95-87, Title 30, Chapter VII, Subchapter K, Section 824.11).

Once outside the mine cut area, the water is transported to the treatment and/or settling location. This is usually accomplished by flexible hose, flexible or rigid pipe (usually plastic, but aluminum, steel, or terra cotta can be used) or trench ditches. When conduits are used, they offer versatility of movement and can readily be transported about the mining area by pick-up truck.

Ditches usually should follow natural contours and may be constructed by backhoe. In some situations, solid rock may be encountered during channel construction, which may require the use of small (but expensive) explosive charges. Care must be taken that the trench is impervious and will not allow the drainage to infiltrate the soil or rock surface. The development of erosion and introduction of further sediment from the ditches are also of concern. If this possibility exists, it may be necessary to line the ditch or to use a conduit. The ditch may be lined with plastic sheeting (about 6-mil or heavier), which is a versatile procedure and relatively inexpensive. These linings will prevent percolation and prevent erosion. They may be moved to other locations for reuse. The location and design of these ditches should take into consideration whether or not it is desirable to introduce oxygen into the water. This determination becomes part of the design for chemical treatment, if necessary. Closed piping minimizes introduction of oxygen into the water, but care must be taken to prevent pipe scaling or sanding.

Design Considerations for Settling Ponds

Design details for sedimentation ponds have been described elsewhere in the literature (Hittman Associates, 1976). Some general considerations are presented here.

Water must be transported to sedimentation ponds to allow solids to settle. These ponds must be adequate in number and have the capacity and design to meet suspended solids and turbidity regulations in their effluent. Thickeners or clarifiers are seldom practical in surface mining operations because of their high cost and the permanent nature of such installations. Where applicable, however, such devices generally will achieve superior results to settling basins. Typically, the sedimentation ponds are located below the low wall at a location that will be adequate to serve during the life of the mine. In some cases, the ponds have been located above the highwall or advancing wall to collect and control surface runoff. This technique may permit reduced pumping distances and results in the removal of the ponds during subsequent mining cuts. Among the design aspects of settling ponds can be a discharge standpipe covered with a screen to trap floating material. The ponds must be designed to permit periodic removal of silt. In some cases, it may be better to allow silt to accumulate until the pond is nearly filled (reducing retention time). At that point, the pond is removed from service and replaced with a newly constructed pond. The new pond may be merely an extension of the original pond, or it may be placed at a more strategic location. The old pond is allowed to dry (by evaporation), it is completely backfilled, and the surface is revegetated. Complete drying of the silt is essential since premature backfilling can push the high-moisture-content fines over the pond sides and possibly result in the introduction of sediment to the stream. This drying process may take months.

Flocculants and other reagents may have to be introduced to pond influent to achieve proper settling.

Frequently coal fines, oil, and other debris such as wood will float on the pond surface and may be discharged with the effluent. This can be avoided or minimized by the distribution of straw on the pond surface. The straw will trap the floating material and collect near the discharge area. The straw can be periodically removed, discarded (buried or burned), and replaced. The floating straw will remain effective until it becomes waterlogged and tends to sink. Replacement cycles may extend from several days to weeks.

Use of Flocculants in Settling Ponds

Most sediment resulting from surface runoff in disturbed mine areas contains clay minerals that are characteristically very fine in size (near colloidal). Their settling behavior would normally be very slow, but these rates are further decreased (often to the point of near permanent turbidity) by virtue of negative surface charges. Various surfactant reagents, generally termed flocculants, can modify these surface charges and permit particles to agglomerate, forming settleable flocs. These reagents vary from highly soluble, ionizable inorganic salts (such as iron and aluminum chloride) to starches, glues, and synthetic organic polymers.

Three procedures are required in the use of these reagents: (1) Establishment of the proper reagent, (2) determination of dosage, and (3) development of appropriate procedures to prepare the reagents and apply them routinely.

Procedures one and two are established empirically by jar tests (Allied Chemical Corporation, 1975; American Cyanamide, 1973; Anis, 1974; U.S. Environmental Protection Agency, 1973). The fresh water test sample (Figure 27) is treated with varying concentrations of reagent (0.01 to 100 mg/ℓ) over a range of adjusted pH values at ambient field temperatures and mixed (slow stirring is preferable to shaking). The sample is allowed to stand quietly, and settling rate measurements are taken (Figure 28) and recorded. The reagents showing the highest settling rates are retested under more carefully detailed conditions to establish optimum performance. Typically, an interface time curve is plotted as shown in Figure 29.

The preparation of the reagent at appropriate concentrations and mixing it to attain the critical concentration (according to the manufacturer's specification) establish the effectiveness of the response. Characteristically, the dilute reagent solution (0.1 percent or lower) is further diluted with the water to be treated and then slowly added. The rate of application is a product of the quantity of water being pumped in per unit of

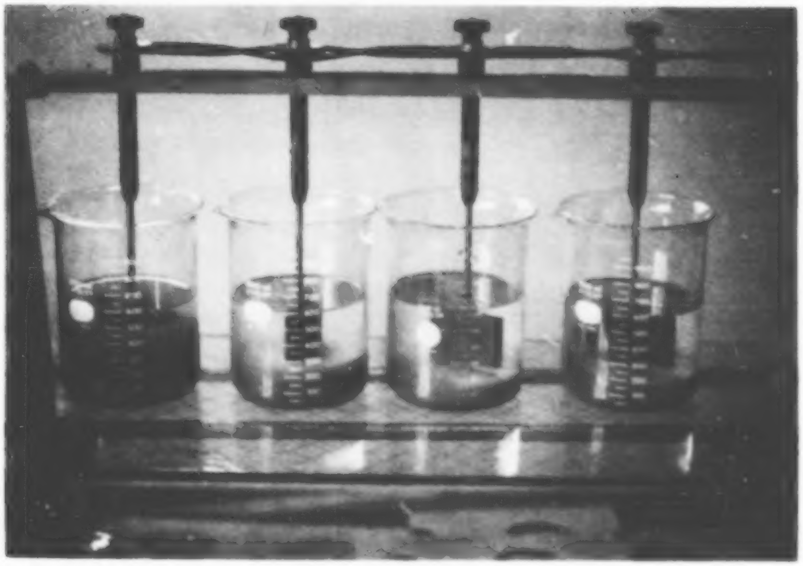


Figure 27. Fresh water samples in jars, ready for testing.

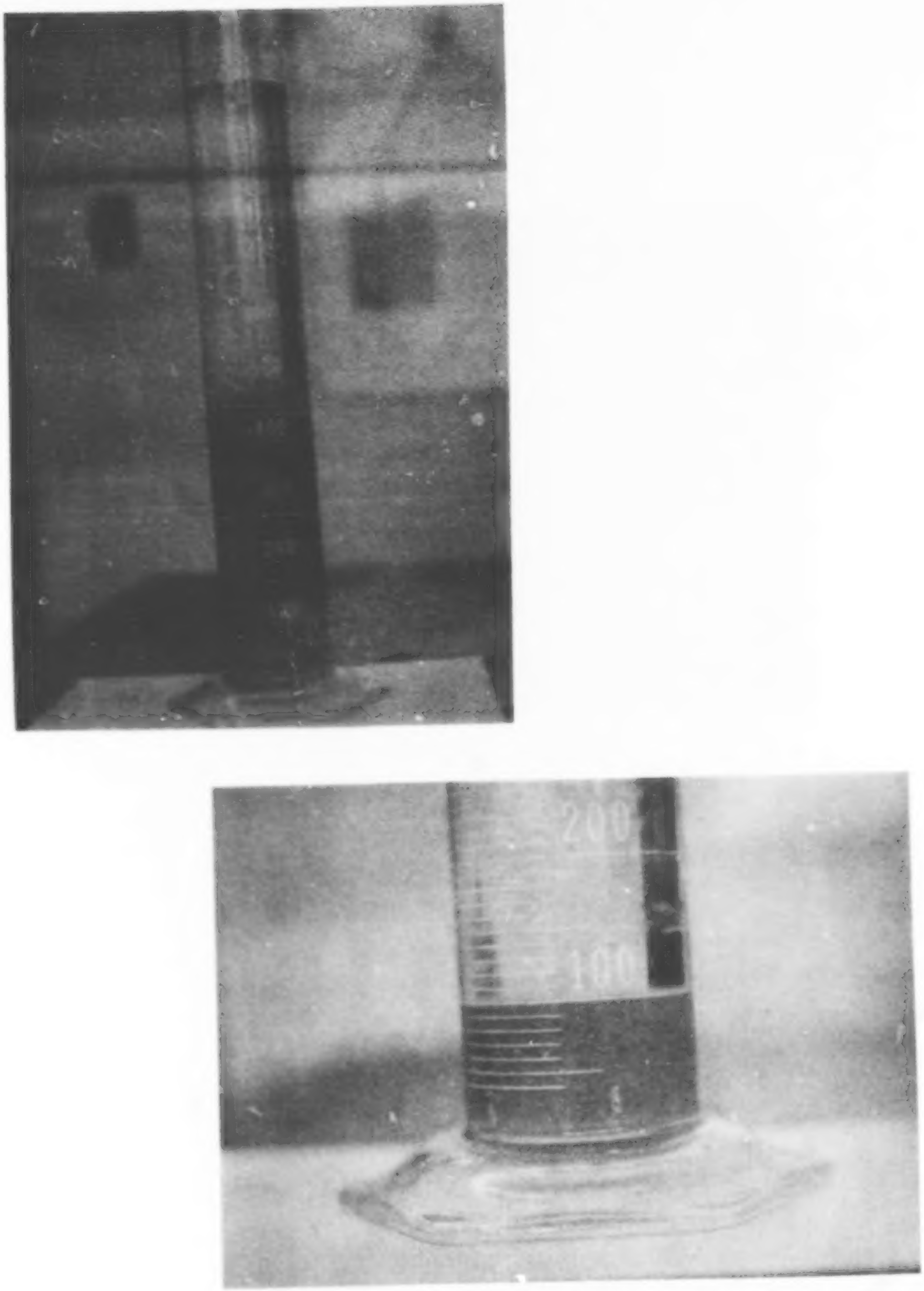


Figure 28. Settling rate measurements of flocculated suspended solids.

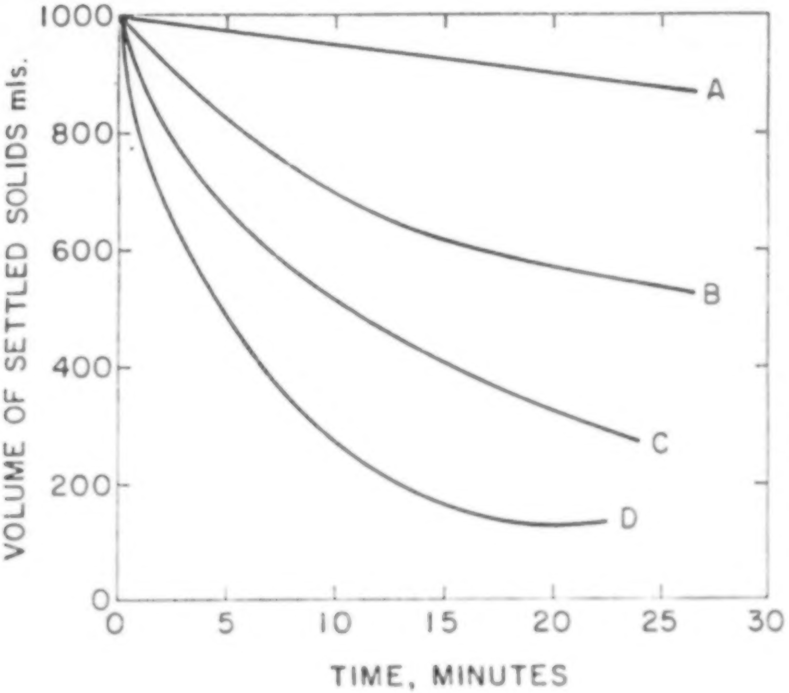


Figure 29. Settling rate curve used in studying the application of flocculants.

time and the desired concentration needed in the water, as determined by the jar test. Flocculants can be added by pumping the predetermined concentration of flocculant solution at the determined rate. The water then proceeds through a slow flocculation mixer, allowing the flocs to form.

The synthetic reagents are long-chained, high molecular weight substances that are deactivated by high-speed mixing, a long period of mixing (> 2 min), or a sudden stop in mixing (Morrow, 1974). Mixing of the reagent with the water to be treated can effectively be accomplished by running the water through a baffled spillway (McCarthy, 1973). Proper mixing has been found to be the most important factor affecting the flocculation process. The treated water is then directed to a settling basin or clarifier for solid/fluid separation.

These reagents are designed to increase settling rates, and they generally do not enhance compaction of the settled solids. Detailed application of Cyanamid Super Floc 330 to surface drainage containing clays from coal mining has been detailed (McCarthy, 1973) and is illustrated in Figure 30.

TREATMENT OF WATERS ASSOCIATED WITH SURFACE MINING

Several approaches can be taken to the treatment of waters collected in pit areas. The initial decision involves establishment of water quality by regular monitoring (when feasible) for pH, acidity, iron, and manganese. If treatment is necessary, there are two basic options: (1) Treatment within the mining pit, or (2) treatment after removal of the water from the pit. The former technique, although seldom used, offers many advantages. Primarily, it reduces the amount of pollutant formation by keeping the waters in an alkaline state. This approach limits any existing unsatisfactory water quality to that entering the mine, and that quality is frequently satisfactory. This procedure also minimizes pump corrosion.

Minimizing the Introduction of Coal Fines and Silt into Waters During Mining

Techniques should be developed to minimize the amount of coal fines that is introduced into the water in collection areas. Often the amount of coal fines introduced into the water is increased if the water is allowed to flow or accumulate in pit areas used as haulways and traversed with trucks or other equipment. Where possible, sump areas should be located away from equipment activity. Sections of drainage ditches traversed by equipment should be replaced with buried pipe. Once created, settling ponds may be employed to remove silt and coal fines from water pumped from open mining cuts. The use of flocculants may also become necessary if concentrations of clay particles are high. Preventive measures are more desirable than the construction of settling ponds and the use of flocculants, which may result in increased total costs.

Figure 30. Flocculated surface waters after clarification from surface mining operation in the State of Washington.

Water Treatment in the Open Cut

Water quality control in the pit is accomplished by the introduction of hydrated lime into the water. After chemical reaction, the formation of sludges and their separation do not pose a problem, since all waters discharged from surface mines must pass through settling basins for sediment control. The lime may be introduced to the pit water as a slurry or by dusting the surface using appropriate equipment. In any case, it is the mixing and solubilization of the lime that become a major concern, since the water depths in surface mine sumps and cuts are usually (or should be) too shallow to permit the use of mechanical mixers. Some mixing can be achieved by intentionally locating the water collection area so it will be traversed by trucks or other moving equipment. This procedure, however, tends to introduce excessive coal fines and silts into the water. The most satisfactory procedure is to cycle the collected sump water through a pump, which insures optimum mixing and efficient use of the lime employed. Such a system permits the introduction of the alkali by broadcasting over the collection area, spraying an alkali slurry into the water, or by attaching a small line from the suction end of the pump to a supply of lime slurry. With this latter method, the pump serves to introduce the lime slurry and circulate the water (Grim and Hill, 1974). Another approach is to fill a drum with an alkali (usually soda ash pellets) and cycle the incoming or sump water through the reagent. Although effective, this system requires frequent attention and is subject to neglect.

Another reagent that has seen little use offers great potential--bag house lime (also known as hot lime or kiln dust). This waste is a byproduct of limestone calcination that is collected to prevent air pollution. It may amount to several percent of the daily kiln production, and it constitutes a disposal problem in itself. In some lime kiln operations, this dust is buried or pumped underground to the limestone mine or rejected into an abandoned quarry. Chemically, the composition of this dust may vary widely, but typically it includes several lime components and ash from the coal fired during limestone calcination. The basicity components are usually about 60 percent calcium carbonate, 30 percent $Ca(OH)_2$, and 10 percent calcium oxide. This byproduct is usually available at handling cost ($2.00 per ton). The economic feasibility of its use depends primarily on transportation costs from the lime operation to the surface mine, which is strictly a function of distance. These waste products are of extremely fine sizes (70 percent are minus 200 mesh), which increase their effectiveness but require bulk transportation by enclosed carrier. The use of rock dust from pulverized limestone can be helpful, especially because of its long-term responses. The rate of response may be limiting.

Treatment of Water after Removal from the Open Cut

Treatment techniques for mine water of unacceptable quality developed during surface mining utilize the same principles and concepts as applied to waters from deep mines and abandoned mine sources (Lovell, 1973, Bhatt, 1973b). Because the distrubed area where the water originates is a temporary and changing location, planning must proceed in accord with equipment portability. Only final settling ponds can be viewed as having any degree of permanence in most of these systems.

Based on anticipated water flow rates and water quality, the basic unit operations that are normally incorporated in the mine water treatment process include:

1. Collection of water and transport to treatment site
2. Neutralization
3. Iron oxidation, if necessary
4. Addition of flocculants, if necessary
5. Solid/fluid separation
6. Controlled release of treated water
7. Disposal of recovered sludge

Most of the engineering concerns methods of reagent introduction, reagent mixture with the water, and settling pond design. The most commonly used reagents are hydrated lime, soda ash, and sodium hydroxide. Seldom does the level of reagent consumption permit bulk reagent purchase and storage. Thus higher reagent costs and higher labor requirements result from the use of bagged reagents. Availability of electric power in a surface mine may be limited, so gasoline-powered generators and hydraulically activated devices are commonplace. The availability of electrical service is a convenience and cost advantage both for the treatment facility and for collection pumps.

The use of soda ash briquettes (Kalb, 1975) (see Figure 31) is most realistic, whereas hydrated lime often creates feeding problems because of material flow stoppage (hang up from moisture absorption). The briquettes are loaded in self-feeding, covered hoppers that permit the water flow to pass through a sluice containing the reagent. Although a commercial device is available, they may be inexpensively constructed from plywood. The water quality and flow control the necessary retention time and briquette accessibility. The slow-dissolving briquettes will maintain the pH at the acceptable levels above 6.0. The labor requirements to ensure continuous and adequate treatment with briquettes are minimal.

The use of hydrated lime is constrained by portable mechanisms for metering of solids. Any reagent is most effectively used as a slurry or solution. Various water-powered devices have been used with small hoppers to dispense hydrated lime directly into a sluice or ditch carrying mine effluent. They tend to be unreliable, however, since the reagent absorbs water and is not introduced uniformly, and it is usually inadequately mixed with the water. Attempts to house such devices, even with the use of heaters or heat lamps, are not much more responsive. Figure 32 illustrates such devices as they are applied in a Maryland operation. More complex devices, such as the Shirley Mix-O-Meter, provide slurrying and reliable metering capability to introduce the reagent, but then require a power source. Lime slurry can also be added to the mine water at the suction end of the pump used to transport water to the settling ponds, as described in the preceding section.

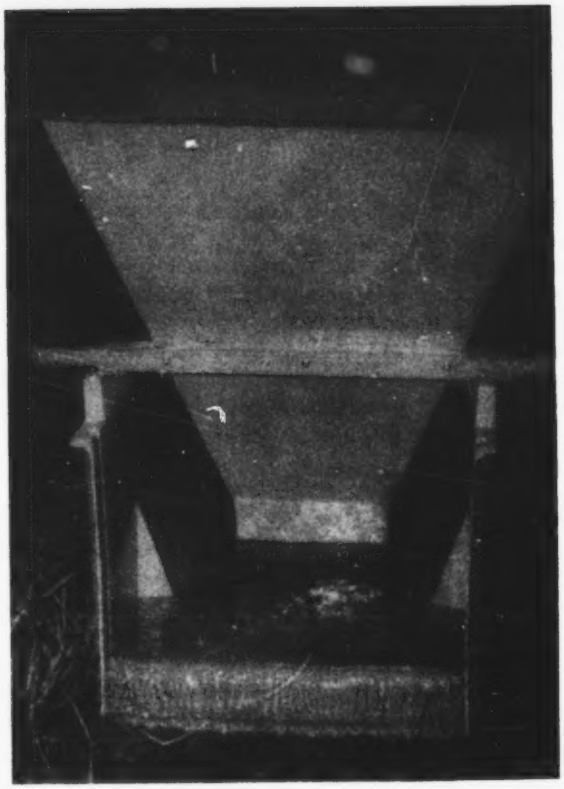


Figure 31. TraDet hopper and sluice used to neutralize mine drainage in surface coal mines.

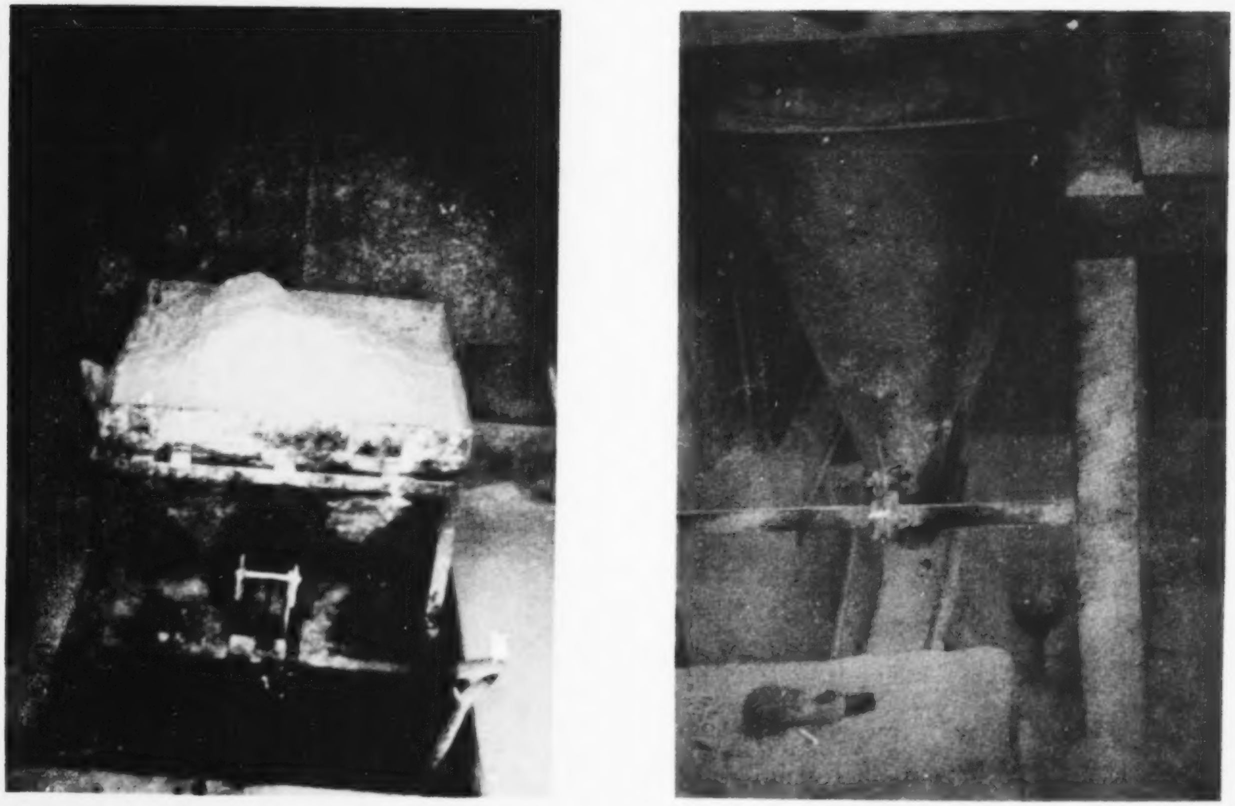


Figure 32. Hopper and metering device for introducing hydrated lime into coal mine drainage.

The use of sodium hydroxide, despite its disadvantages (it is costly, hazardous, and difficult to store), has special advantages in the treatment of waters in surface mining. Its advantages are based on the versatility it derives from its distribution as a concentrated solution. Accordingly, it may be continuously pumped for accurate dosage control from drums at remote locations. The advantages, disadvantages, and use of the reagent have been detailed (Lovell, 1973).

Limestone tends to be unsatisfactory in water treatment under most conditions experienced in surface mining (Lovell, 1973). Limestone is frequently cited as being less reactive than hydroxide reagents. This constraint is related to limestone's limited solubility and the development of carbonate-bicarbonate equilibria rather than chemical reactivity. Such systems often show a limiting pH less than 6.0. However, by adequate system design to permit removal of carbon dioxide, higher pH levels can be maintained. Drainage water containing ferrous ions may be inadequately responsive when treated with limestone due to solubility products constraints of ferrous hydroxide. Limestone use requires the construction of a reaction vessel, such as a rotary drum or flash mixer, to provide continuous mixing of the limestone with the water. This step not only increases the neutralization capability of the limestone, but abrasion also removes surface coatings on the limestone that result from the neutralization reactions. The liberal use of this least expensive reagent is frequently helpful during several stages of reclamation, in lining waterways, and even in active pit operations.

Treatment of mine drainage by a combination limestone-lime process has been shown to offer several advantages over limestone treatment (Wilmoth and Kennedy, 1976). However, the limitations cited above for the use of limestone still apply.

The need to oxidize ferrous iron as a water treatment step is seldom experienced in surface mining, although the same principles are applicable as described elsewhere (Lovell, 1973). Attempts to pond water from active cuts and cultivate the growth of iron oxidizing bacteria have been reported in Pennsylvania (see Figure 33). Other techniques attempt to incorporate air into the water. This goal may be accomplished by creating turbulent flow through the use of a baffled spillway.

Sludge disposal following alkali treatment also involves the same control measures previously described (Lovell, 1973). The main factors are adequate retention time, sludge removal, and final disposal. Figure 34 shows settling ponds separating ferruginous sludges after lime treatment in an abandoned Pennsylvania surface mine.

The most critical requirement in surface coal mine drainage treatment is proper monitoring of the clarified effluent. Beyond the interim grab samples required by regulating agencies, continuous monitoring is generally not practiced. Continuous pH monitoring is relatively inexpensive and reliable, equipment is available, and little maintenance is required. Continuous pH monitoring provides reliable indications for adequate effluent quality, since proper pH levels can be related to laboratory grab sample data

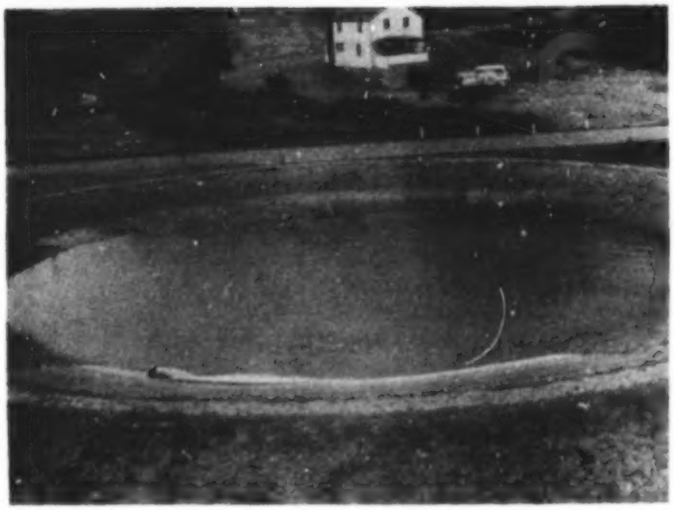


Figure 33. Ponded mine drainage designed to cultivate the growth of iron-oxidizing bacteria as a water treatment operation.

for alkalinity and dissolved iron. It is also feasible to monitor continuously for suspended solids (or turbidity) and for conductivity as a measure of total dissolved solids.

Alarms can be provided in the continuous monitoring systems that alert any tendency toward inadequate effluent quality. Further safeguards can be introduced by the inclusion of a discharge control valve that will close on a pH signal to prevent the discharge of unacceptable effluents.

Carbonate Rocks Added to Acid Water

The three important reactions in the neutralization process were reported by Barnes and Romberger (1968):

$$H^+ + CaCO_3 \rightarrow Ca^{2+} + HCO_3^-$$

$$\log (K_{25^\circ}) = +2.0 \qquad (1)$$

$$HCO_3^- + H^+ \rightarrow H_2CO_3$$

$$\log (K_{25^\circ}) = +6.4 \qquad (2)$$

$$H_2CO_3 \rightarrow H_2O + CO_2(g)$$

$$\log (K_{25^\circ}) = +1.5 \qquad (3)$$

The secondary reactions given in equations 2 and 3 take place only below a pH of about 6.4, but reaction 1 can proceed at every pH up to a point slightly above pH 8, where solid $CaCO_3$ is stable with the solution in equilibrium at normal atmospheric pressure (pressure of CO_2 about $10^{-3.5}$ atm).

These reactions would apply in cases where limestone fragments penetrate the spoil bank and enter standing groundwater near the base of the spoil. In time, insoluble ferric hydroxide would be precipated out on the surface of limestone particles. This armoring effect slows further reaction of the calcium carbonate with the acid, and the neutralization reaction should slow or might even stop after a short time.

Role of Dilution--

The pH of acid water can be raised both by simple dilution and by buffering when it is mixed with water containing various concentrations of

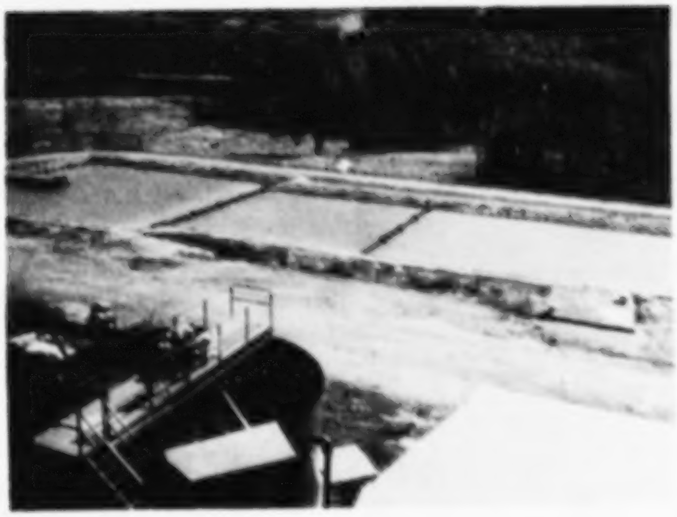


Figure 34. Solid/fluid settling basins to remove sludge from lime-treated surface mine drainage.

HCO_3^-. Figure 35 shows the pH change as a function of dilution when the diluent is free of bicarbonate and has a pH of 7, which might be the case for rainwater.

The equation for the curves at low initial pH (linear segments of the curves) is:

$$pH_2 = pH_1 + \log (X) \tag{4}$$

where pH is given for the two waters, and X is the ratio of the final to initial volume of water (Barnes and Romberger, 1968).

For example, if 1,000 volumes of water at pH 3 are diluted to a final volume of 100,000 volumes, X is 100, and the final pH would be 5. The curves for higher initial pH are complicated by the contribution of H+ by the diluent.

Role of Neutralization--

Water containing bicarbonate is much more efficient in neutralizing acid water than bicarbonate-free water; much less diluent is necessary for neutralization to take place. Equations 5 and 6 are involved (Barnes and Romberger, 1968).

Figure 36 presents a series of diagrams showing for different concentrations of bicarbonate in the diluent the initial and final pH relations as a function of dilution. Three equations describe these curves:

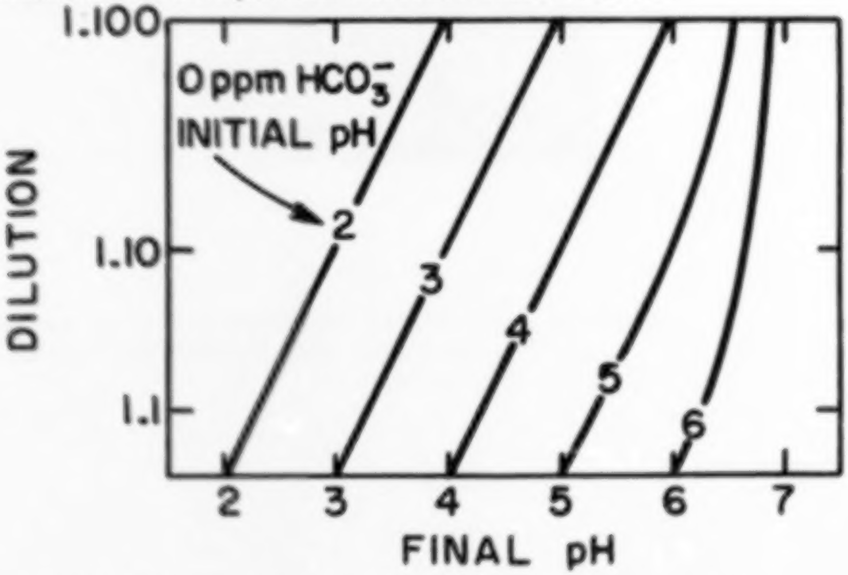


Figure 35. Effect of dilution on the pH of mine waters when mixed with bicarbonate-free water with a pH of 7 (Barnes and Romberger, 1968).

$$(M_{H+})\ \text{final} = [(M_{H+})\ \text{initial}\ (XD)] - [(M_{HCO_3^-})\ \text{initial}\ X(1-D)] \qquad (5)$$

$$(M_{H+})\ \text{final} = \frac{10-11.37}{[(M_{HCO_3^-})\ \text{initial}\ X(1-D)] - [(M_{H+})\ \text{initial}\ X\ D]} \qquad (6)$$

$$\text{pH} = -\log\ (M_{H+}) \qquad (7)$$

where (M_{H+}) final and (M_{H+}) initial are the final and initial concentrations of H^+ in moles per 1,000 g of water, D is the dilution (the ratio of initial to final volume), and $(M_{HCO_3^-})$ initial is the initial concentration of HCO_3^- in the diluent in moles per 1,000 g of water.

$$M_{HCO_3^-} = (1.64 \times 10^{-5}) \times \text{mg/}\ell\ HCO_3^- \qquad (8)$$

Equation 5 applies to the portion of the diagram where the final concentration of H^+ exceeds that of HCO_3^- after dilution, and equation 6 applies to the portion where the final concentration of HCO_3^- exceeds that of H^+ after dilution.

For example, with a diluent containing 10 mg/ℓ HCO_3^-, an acid water of pH 3 must be diluted 1:10 to reach a final pH of 7. Slightly greater or smaller dilutions than those found from these curves might be required because of variations in activity coefficients and minor buffering reactions resulting from other components of natural waters.

Fortunately there is a critical level of dilution for any initial pH and HCO_3^- content of the diluent that corresponds to the horizontal portion of the curves of Figure 36. Near this critical ratio, very small changes in the degree of dilution have major effects on the effluent pH. The critical ratio is caused by buffering by HCO_3^- and is important only above bicarbonate concentrations in the diluent of roughly 25 mg/ℓ (Barnes and Romberger, 1968).

Both reaction with carbonate rocks and dilution with bicarbonate-containing water are effective techniques for treating acid waters to raise the pH. Both water quality changes and resulting solid precipitates must be considered. In the case at hand, amorphous ferric hydroxide hydrates (yellowboy) should be precipitated out within the spoil materials. This commonly occurs within streambeds, hence this problem should be alleviated once limestone is applied.

Depending on conditions encountered, gypsum ($CaSO_4 \cdot 2H_2O$) may precipitate. This reaction is rare in mine drainage, but it occurs in mine tailings. A white hydrated aluminum oxide may form when pH rises slightly above 5.

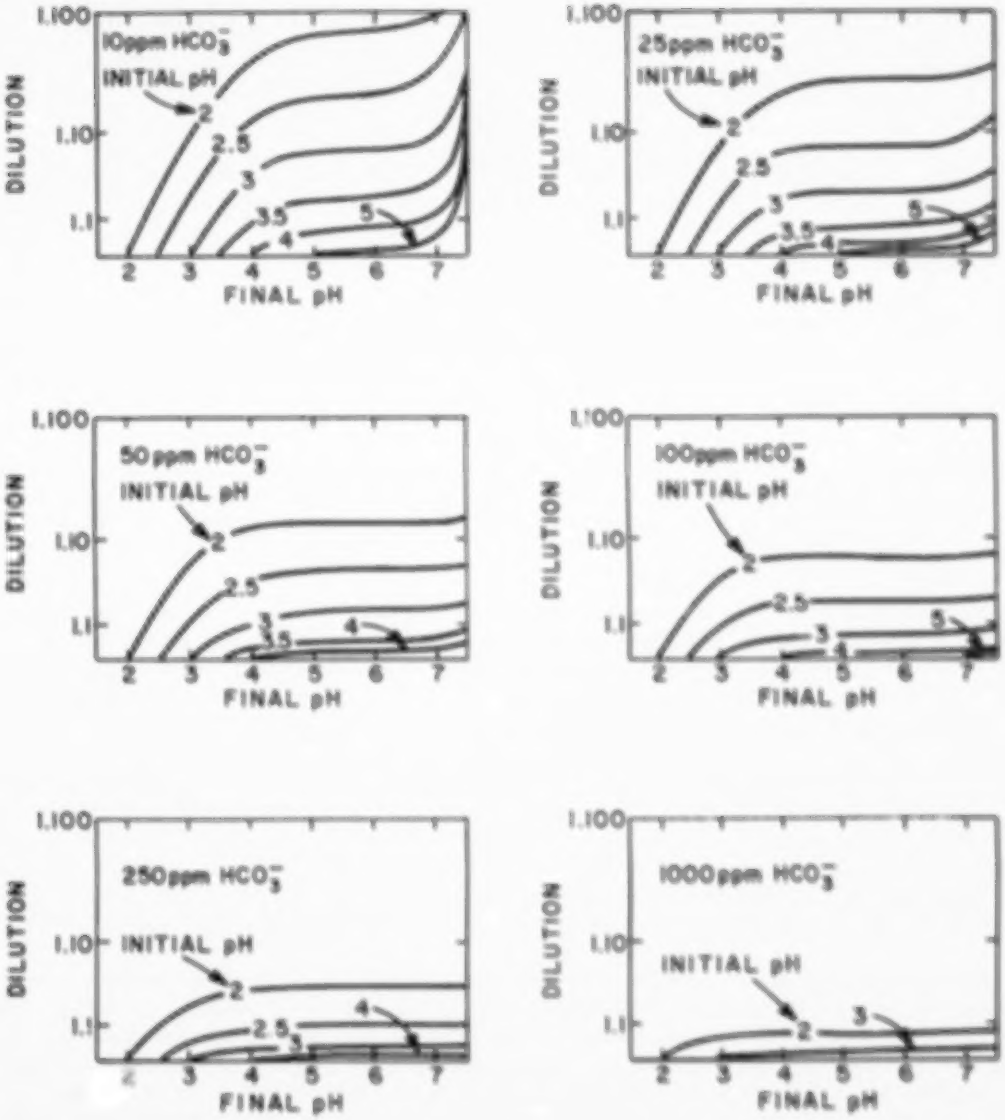


Figure 36. The combined effects on mine water pH of dilution and buffering by mixing with bicarbonate solutions of six different concentrations (Barnes and Romberger, 1968).

The final effluent may contain quantities of sulfate (over 250 mg/ℓ), suspended solids (5 mg/ℓ, unless it accumulates within the waste rock), magnesium (125 mg/ℓ as $CaCO_3$), and total dissolved solids (500 mg/ℓ)(Biesecker and George, 1966; Hem, 1960). Any dilution by ground and surface water soon will bring the quality of treated water up to acceptable concentrations. Any neutralization that can be achieved onsite will be an improvement.

These chemical mechanisms can be exploited by the selective placement of alkaline-producing soil and rock above acid-forming minerals. Such strategy requires that a mineralogical and geochemical profile be established for the soil and rock overburden deposits to plan the mining process and select proper equipment. Calcareous glacial till, loess, outwash, etc. may be stripped separately from acid-producing bed rock strata. Where glacial drift blankets bed rock spoil following mining, little or no acid and iron drainage problems result. However, such may not be the case where spoil deposits are mixed during the mining process and carbonate rock fragments are not abundant. The surface area of unconsolidated overburden soils is far greater than that of fragmented bed rock, hence calcareous shale and thin limestone beds should be selectively stripped and placed where they will have the greatest benefit in the backfill (Figures 37 and 38). Often large blocks of marine and fresh-water limestone are contained in mine spoil. Thin beds of limestone typically break along bedding and joint planes or part along solution-enlarged openings. Often these are coated with iron hydroxides and probably are limited in their bicarbonate-producing potential.

Blocky limestone might be selectively stripped and crushed, and the aggregate carefully placed near the top of mine spoil to improve the ground-water quality where acid reactions are inevitable (Figure 39). This added step taken during mining could go a long way toward reducing mining and post-mining acid drainage problems.

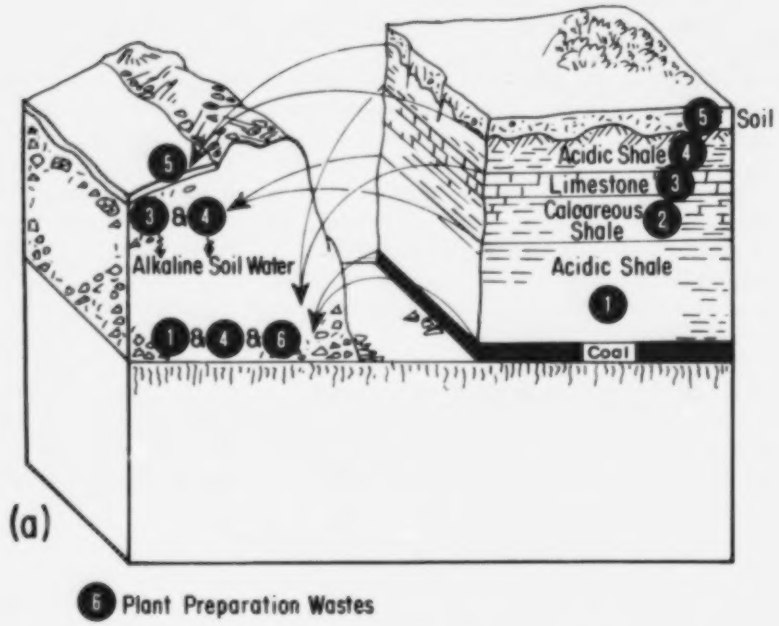

Soil
5
Acidic Shale
4
Limestone
3
Calcareous Shale
2
Acidic Shale
1
Coal
5
3 & 4
Alkaline Soil Water
1 & 4 & 6
(a)
6 Plant Preparation Wastes

Figure 37. Limestone and calcareous shale placed on top of acid-producing strata to impede acidic reactions. Top soil restoration promotes rapid revegetation and productive use of reclaimed lands.

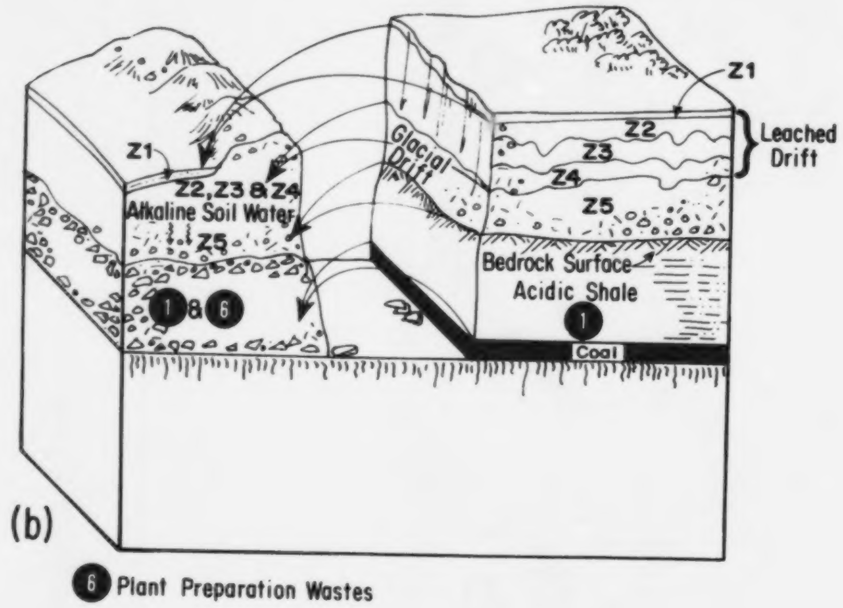
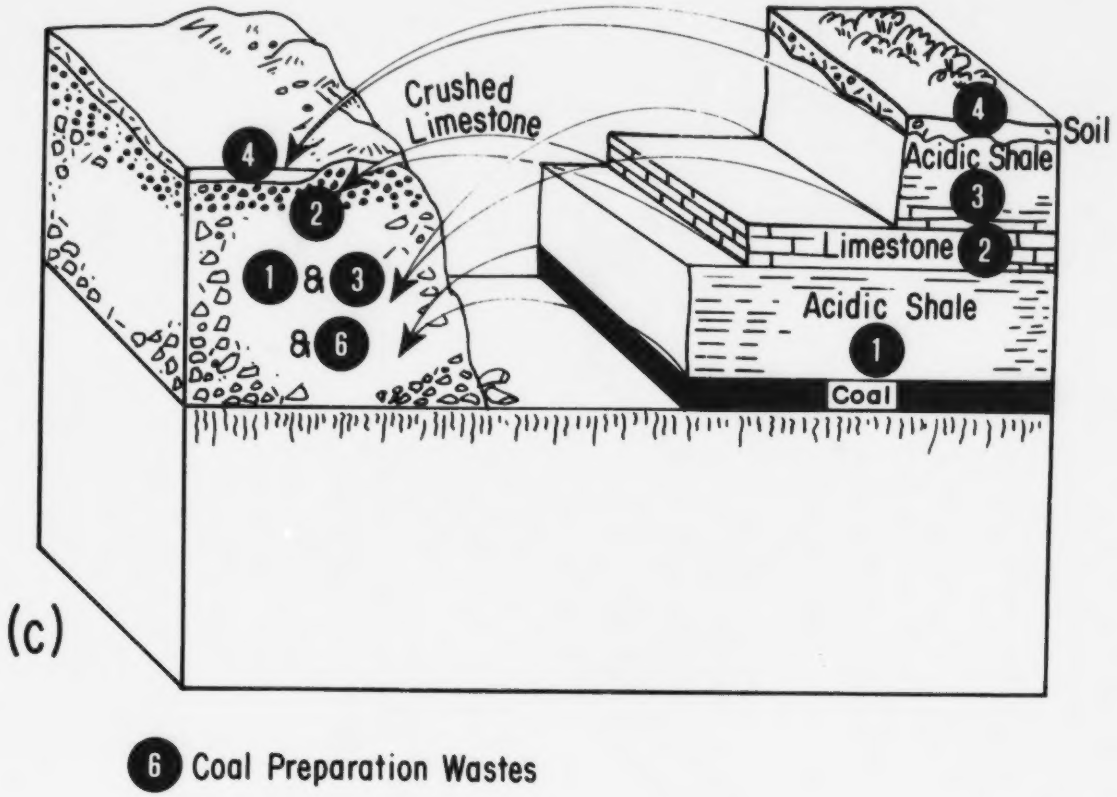

Z1
Z2
Z3
Z4
Z5
Leached Drift
Glacial Drift
Z1
Z2, Z3 & Z4
Alkaline Soil Water
Z5
1 & 6
Bedrock Surface
Acidic Shale
1
Coal
(b)
6 Plant Preparation Wastes

Figure 38. Glacial drift overburden is placed upon bed rock spoil: the unleached Z5 horizon impedes acid reactions within underlying rock spoil deposits. Topsoil is reclaimed to stimulate plant growth and retain oxygen migration.



Crushed Limestone
4
2
1 & 3
& 6
(c)
4
Soil
Acidic Shale
3
Limestone
2
Acidic Shale
1
Coal
6 Coal Preparation Wastes

Figure 39. Thin, blocky limestone beds crushed to increase surface area and placed above acid-producing mine spoil and coal plant preparation wastes. Note: No calcareous shale unit is present in this example.

SECTION 5

EXPERIMENTAL TECHNIQUES FOR TREATING SURFACE MINE WATERS

OVERVIEW

Significant progress has been achieved by numerous researchers experimenting with new methods of treating and controlling surface mine waters. This section presents a brief review of these recent accomplishments. The discussion that follows organizes current research efforts into three major groupings: physical/chemical plant processes, chemical field methods, and physical field methods.

PHYSICAL/CHEMICAL PLANT PROCESSES

Recently, more sophisticated techniques have been applied to physical/chemical plant processes for the treatment of mine drainage waters. The treated water is of a near potable quality, and in some instances it has been used as part of municipal supplies (Kunin, 1974). The processes require much more elaborate installations than needed for treatment by neutralization, but in some instances they may be applicable. Two of these processes, ion exchange and reverse osmosis, are briefly discussed below.

Ion Exchange

The ion exchange process removes the objectionable metal salts and hydroxides from the mine water by replacement with ions from an ion exchange resin. As the resin becomes exhausted, replacement capability decreases, and regeneration of the resin is necessary.

Various forms of ion exchange processes can be used to remove constituents from mine drainage. Either alone or in combination with neutralization, softening, and aeration, ion exchange can produce water of high quality suitable for either domestic or industrial use. Indications are that the sludges and other residues produced by this process may be more amenable to disposal than those produced by neutralization (Bhatt, 1973a and b).

Two major limitations exist to the application of this process: (1) The process requires sophisticated portable equipment that requires continued maintenance by trained personnel; and (2) the relatively high cost of the regeneration chemicals makes the process uneconomical compared with alternative processes after the total solids level exceeds 500 to 1000 mg/ℓ (Bhatt, 1973a and b).

Two criteria can be used in selecting ion exchange processes for the treatment of mine drainage (Bhatt, 1973a and b):

1. Ability to convert the contaminating soluble ions present in mine drainage into insoluble forms.
2. Ability to utilize low-cost chemicals as regenerants or to develop process sequences that allow for the recovery and reuse of the regenerant.

Reverse Osmosis

The nearly complete removal of metal salts from mine drainage is accomplished in reverse osmosis by the movement of the water through a semipermeable membrane leaving a concentrated solution of salts. The equipment involved in this process is extremely elaborate, and many problems have been encountered when treating acid mine drainage (Blackshaw, 1974). The major disadvantages of this process include (Bhatt, 1973a and b).

1. Acid mine drainage treatment and brine disposal are costly.
2. Reverse osmosis by itself does not eliminate acid mine drainage water.
3. Membranes foul and consequently require periodic replacements.
4. Operation with acid solutions required for the prevention of scaling makes it necessary to construct the plant of corrosion-resistant materials that significantly increase capital cost requirements.
5. Prefiltration of acid mine drainage is required for feed to a reverse osmosis process unit.

The only reported principal advantage of reverse osmosis for acid mine drainage treatment is the recovery of nearly potable water as a byproduct (Bhatt, 1973a and b).

CHEMICAL FIELD METHODS

Three methods are reported under this grouping. They include the use of soil as a renovation medium, the application of sewage sludge and effluents, and the use of limestone barriers.

Soil as a Renovation Medium

Calcareous Soils--

Soil leached of carbonate minerals (calcite and dolomite) will not provide a buffer capacity to acid mine drainage, as outlined previously. Most residual and transported soil deposits that make up the A and B soil horizons have been leached of carbonates in humid regions. Calcium carbonate, gypsum, and other soluble salts can be enriched within the B-Horizon of soils forming in arid and semi-arid regions, but these occurrences should be rare within the eastern mining districts.

"Soil" by the engineering definition (i.e., any naturally occurring aggregate of material that can be disaggregated by gentle mechanical means such as stirring in water) can contain important reserves of carbonate minerals located below the zone of leaching. Loess, glacial till, outwash sand and gravel, and lacustrine deposits typically are calcareous below the zone of leaching. These deposits can be identified during prospecting, and selectively stripped and placed during mining, provided that their presence and value in neutralizing acid reactions are recognized in premining planning studies. They can be more effective in offsetting acid reactions than artificially applied crushed limestone because of the vast surface area that spoil particles afford compared with crushed aggregate. Glacial deposits, derived in part from the erosion and transport of calcareous bed rock, typically contain calcareous minerals in all grain-size fractions and are common as silt- and clay-size particles.

These soils should be identified and characterized in premining planning studies and included where possible in mine restoration plans so that they will give the maximum benefits in offsetting acid reactions or abating acid mine drainage where formed. The slow leakage and migration of acid mine drainage into soils of this type can result in long-term treatment benefits that may not have been anticipated (Figure 40).

Calcareous soils might be exploited in a number of ways. The most advantageous use of these soils should be as a top dressing on acid-producing bed rock, where there should be pronounced suppression of the acid-forming chemical reactions, as explained previously.

If acid mine drainage has been produced and then comes in contact with calcareous soils naturally or is applied to the soil by deliberate flooding or spray irrigation (Figure 41), it will only be a matter of time before the neutralization potential of the soil is consumed and the pollution front continues to migrate within the soil water and groundwater flow systems.

If surface treatment procedure is adopted, lime application would be required to maintain a favorable treatment soil environment. A pH adjustment would result, but the byproduct water would (1) increase in total hardness, (2) contain sulfates (a byproduct of the acid-forming reactions) unless it were precipitated as the mineral gypsum, and (3) have a high specific conductance.

Noncalcareous Soils--

Caution should be exercised when applying highly acidic water to soil and rock where neutralization reactions are not likely to occur. Many trace elements and heavy metals can be leached from natural soil and rock deposits at low pH values. These elements, previously present in trace amounts in soil water and groundwater, could increase dramatically and seriously contribute to the total pollution problem. The interaction of acid water with clays, feldspar, and related minerals can account for partial renovation of acid mine drainage, which should cause the pollution front to lag behind the actual groundwater and soil water flow rate.

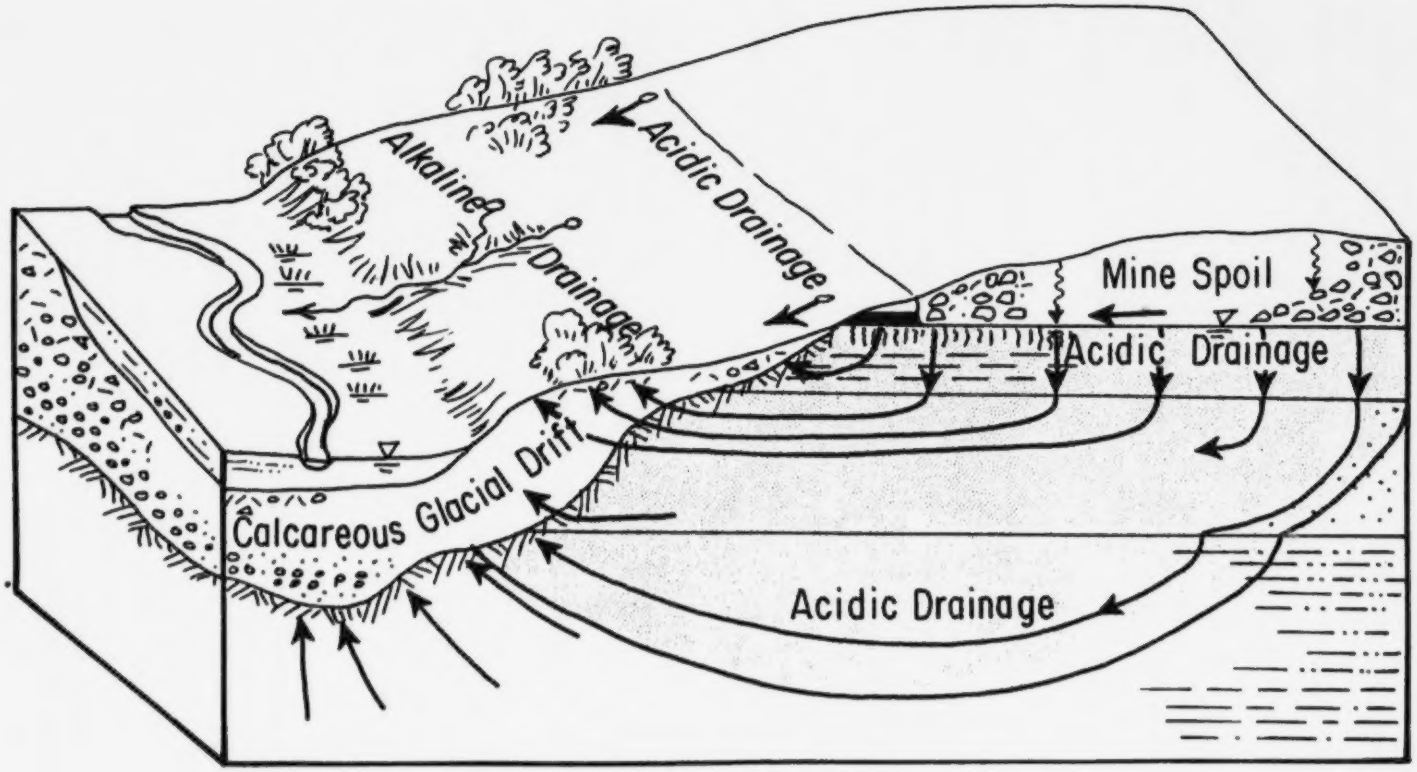

Alkaline Drainage
Acidic Drainage
Mine Spoil
Acidic Drainage
Calcareous Glacial Drift
Acidic Drainage

Figure 40. Natural abatement of acid mine drainage where acidic groundwaters come into contact with calcareous soils.

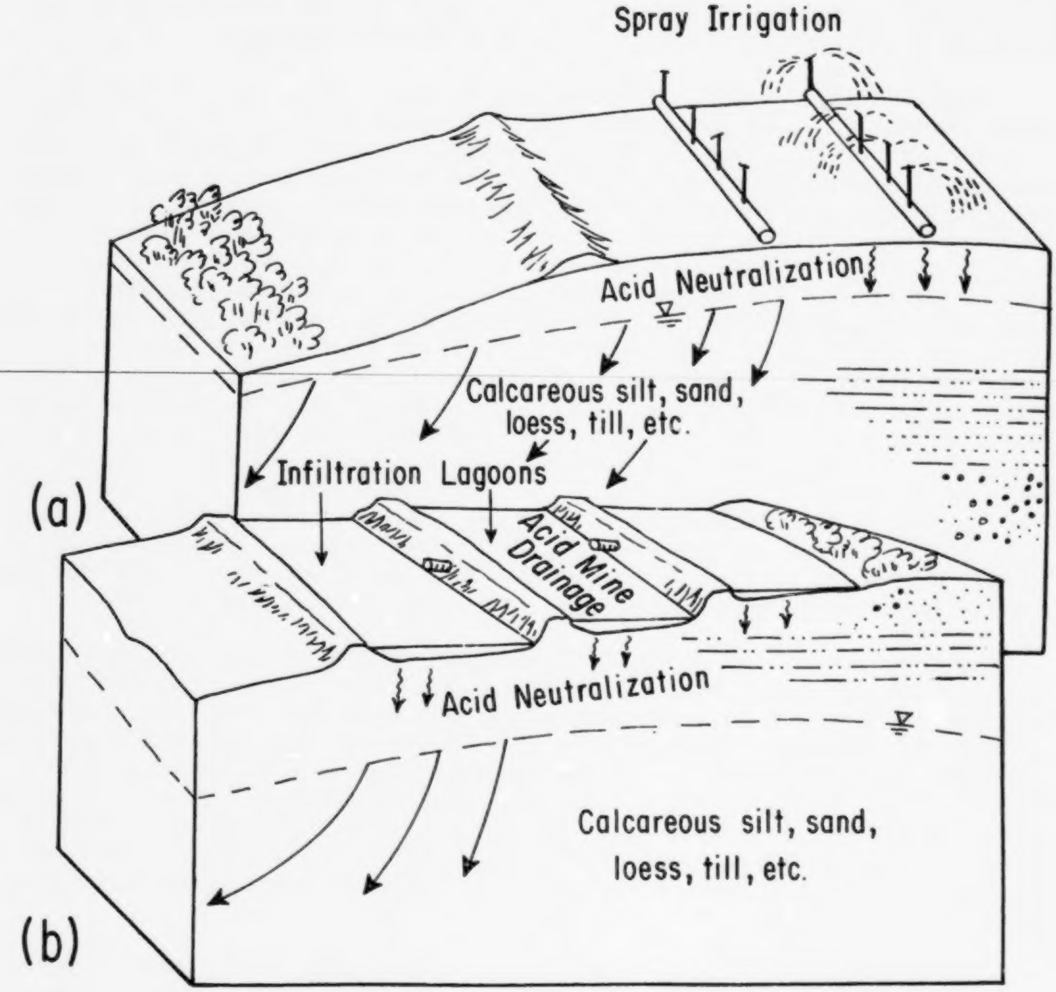

Spray Irrigation
Acid Neutralization
Calcareous silt, sand, loess, till, etc.
Infiltration Lagoons
(a)
Acid Mine Drainage
Acid Neutralization
Calcareous silt, sand, loess, till, etc.
(b)

Figure 41. Application of acid mine drainage to calcareous soils by spray irrigation (a) and flooding methods (b).

Little work has been done to assess the soil's renovation potential for acid mine drainage. Recent laboratory field experiments at The Pennsylvania State University show that benefits are possible under some circumstances.

Beers, et al. (1974) tested initial soil columns in the laboratory through which mine drainage was leached. Rayne and Guernsey soils were selected to construct 102-cm (40-in) soil profile columns. These soils are found extensively in coal-producing regions of Pennsylvania, Ohio, West Virginia, and Kentucky. Once a week for 42 weeks, 13 cm (5 in) of acid mine drainage was added to the columns and leachate samples were tested for a range in constituents typically found in acid mine drainage.

Table 9 shows selected chemical properties of these two soils. Mine water showed increases in pH after it percolated through both soil columns (Figures 42 and 43). The pH of water applied ranged from 2.6 to 2.8, and the percolate rose to approximately 4.0 for the Rayne soil and 8.1 for the Guernsey soil. The researchers conclude that the high effluent pH for the Guernsey treatment was due primarily to the neutralization of acid by limestone material in the Guernsey subsoil (Table 9). The Rayne soil was not calcareous but had a near neutral pH within its surface horizon (Table 9). Both soil columns show the residual effects of agricultural lime applications during past farming activities to a depth of 23 cm (9 in). Beers et al. (1974) conclude that the increase in pH for the Rayne treatment is probably due to the interaction of the acidity in the water with the ions on the organic and inorganic exchange complex as well as direct reaction with soil material. Residual limestone particles in the surface horizons of both soils may have contributed to the neutralization of acidity in the initial leaching. They suggest that an equilibrium condition was established during the study in which the pH was dependent on the soil type. Neutralization capacity remained constant for the Guernsey soil, whereas it showed a slight decrease for the Rayne soil after 419 cm (165 in) of acid water was applied.

The Rayne effluent contained filterable acidity throughout the leaching study, which increased after the addition of 419 cm (165 in) of acid water; whereas the Guernsey effluent showed filterable acidity only during the first half of the experiment (Figure 43). This response, they conclude, probably resulted from the saturation of the exchange complex with hydrogen and aluminum ions, which caused a reduction in the ability of the soil to remove these acidic ions from solution. The Rayne soil was acidic and must have relied on cation exchange and hydrolysis reactions to neutralize acidity, and to a lesser extent on neutralization by limestone fragments (Beers et al., 1974).

It is important to note that aluminum, manganese, zinc, copper, potassium and magnesium also were reduced within the soil columns to varying degrees. The Guernsey soil decreased aluminum content 100 percent throughout the study, and the Rayne soil showed a significant but varying reduction (Figure 44). Aluminum increased as the fiterable acidity increased during the 33 weeks or after application of 419 cm (165 in) of mine drainage. Thus aluminum solubility increases with soil acidity. For the initially favorable pH Rayne soil, aluminum reduction is accounted for by absorption on the exchange

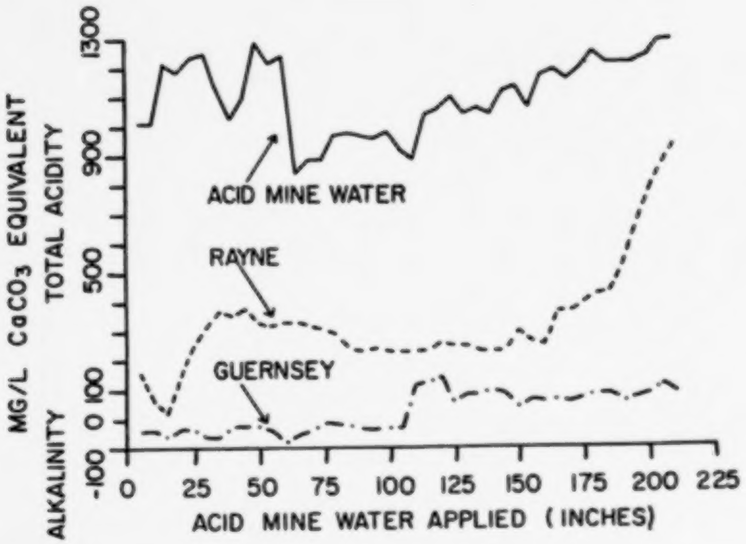


Figure 42. Comparison of pH for acid mine water and Guernsey'and Rayne column effluents. (Source: Beers et al., 1974).

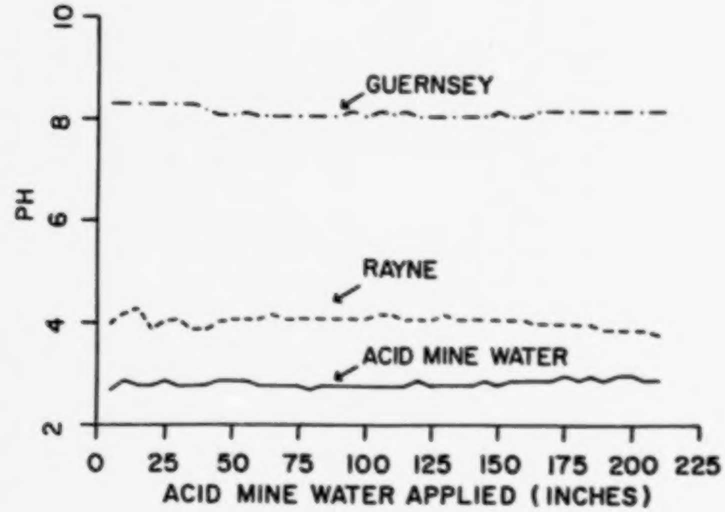


Figure 43. Total acidity or alkalinity of acid mine drainage and Guernsey and Rayne soil column effluents. (Source: Beers et al., 1974).

TABLE 9. SELECTED CHEMICAL PROPERTIES OF RAYNE AND GUERNSEY SOILS*

Soil horizon and lab no.†	Depth (in.)	pH	Exchangeable cations (meq/100g)					Organic carbon (%)	Base sat. (%)	$CaCO_3$ equiv. (%)
			Al	Ca	Mg	Na	K			
					Rayne					
Ap (56-2-1)	0-9	6.1	0.3	9.0	0.3	0.06	0.34	1.83	44.6	1.4
B21 (56-2-2)	9-17	5.4	1.2	4.7	0.1	0.06	0.19	0.37	21.7	0.0
B22t (56-2-3)	17-26	4.9	5.9	2.7	0.1	0.04	0.21	0.18	18.2	0.0
B23 (56-2-4)	26-38	4.8	6.5	1.9	0.1	0.04	0.21	0.05	12.8	0.0
B24 (56-2-5)	38-51	4.8	6.5	1.3	0.1	0.05	0.35	0.05	10.3	0.0
					Guernsey					
Ap (63-6-1)	0-9	6.2	0.1	11.4	0.7	0.20	0.30	1.84	59.2	1.5
B21t (63-6-2)	9-18	4.9	3.8	9.5	0.9	0.20	0.05	0.14	39.4	0.0
B22t (63-6-3)	18-23	4.2	3.5	12.7	1.1	0.20	0.40	0.11	50.7	0.0
B23t (63-6-4)	23-27	5.5	0.0	23.8	1.4	0.20	0.40	0.12	71.9	2.0
B24gt (63-6-5)	27-33	6.7	0.0	26.0	1.1	0.20	0.30	0.18	100.0	5.0
Cl (63-6-6)	33-40	7.4	0.0	30.8	0.7	0.20	0.20	0.13	100.0	8.8

*Source: Beers et al., 1974.
†Pennsylvania State University Soil Characterization Laboratory number.

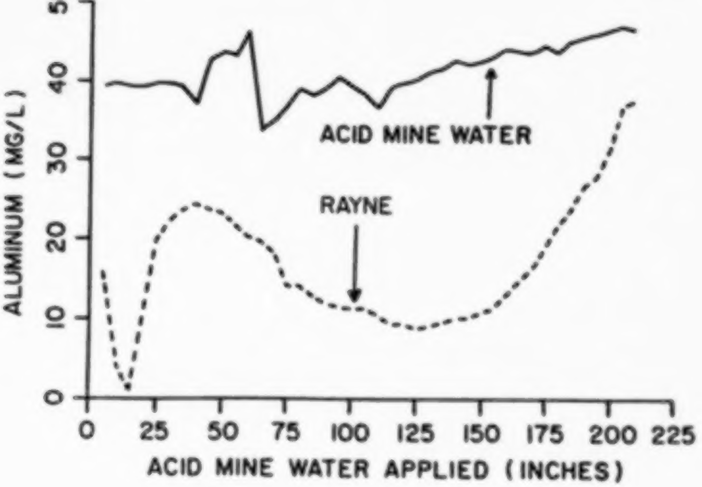


Figure 44. Aluminum content of acid mine water and Rayne soil column effluents (Source: Beers et al., 1974).

complex until exchange positions become saturated with aluminum ions, whereas with the higher pH Guernsey soil, aluminum was completely removed as aluminum hydroxide precipitates (Beers et al., 1974).

Iron concentrations ranged from 150 to 350 mg/ℓ in the 533 cm (210 in) of applied mine drainage, but no iron appeared in the percolate. Iron is very sensitive to pH and Eh conditions, and the researchers report that the soil columns were aerated enough to oxidize ferrous iron to the ferric state within the pH ranges encountered (Rayne, pH 4 and Guernsey, pH 8). Iron would have precipitated as $Fe(OH)_3$ or absorbed on exchange sites (Beers et al., 1974). The role of available oxygen in reducing the ferrous iron content of acid mine drainage can be appreciated by tracing the migration of mine water within stream channels. $Fe(OH)_3$ precipitates within the streambed reveal a reduction in dissolved iron. Yellowboy accumulations within spring pools and groundwater seepage areas also show that oxygen is available to oxidize and precipitate ferric iron at the groundwater/atmospheric interface.

Manganese removal was similar to that of aluminum. It is also dependent on pH and Eh, and it is influenced by the availability of carbonate anions (Krauskopf, 1967). Beers et al. (1974) report that the higher the soil pH and oxidizing state, the greater the tendency for manganese to precipitate as a hydroxide (possibly a carbonate) as well as to be absorbed on the exchange sites (Figure 45). The more acidic Rayne soil removed manganese by absorption on exchange sites until they become saturated after 152 cm (60 in) of mine drainage was applied to the 102-cm (40-in) long soil columns. After 254 cm (100 in) was applied, the manganese content of the Rayne percolate was higher

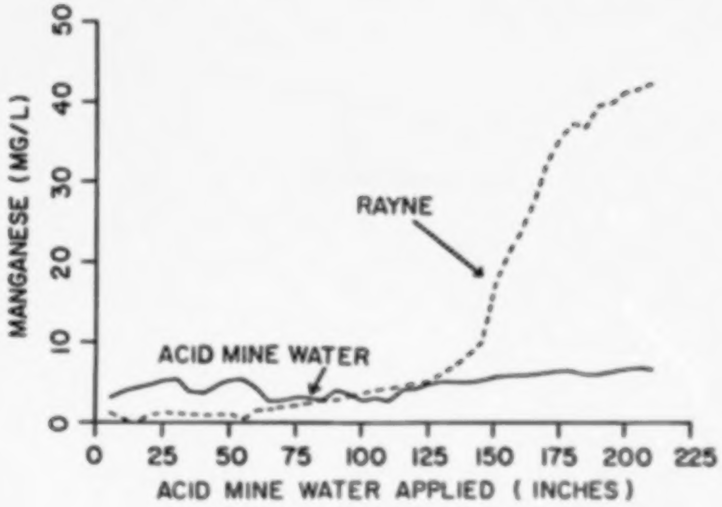


Figure 45. Manganese content of acid mine water and Rayne soil column effluents (Source: Beers et al., 1974).

than that of the applied mine water, which indicates that as the pH fell, manganese was being stripped from the soil column (Beers et al., 1974) (Figure 45). This result illustrates an important concept: metals may be leached from soil and rock by soil water and groundwater flow systems under low pH conditions even at somewhat remote distances from the mine site.

Zinc removal was similar to that of manganese and is also pH dependent for the Rayne soil. Zinc concentration declined in the Rayne effluent until absorption sites were filled; then it increased rapidly and exceeded initial values in the mine water, revealing that it was being leached from the soil column as pH values began to decline. The more alkaline Guernsey soil removed zinc at a fairly steady rate throughout the experiment (Figure 46), probably as a carbonate or hydroxide precipitate (Krauskopf, 1967; Beers et al., 1974).

Copper content of the effluent from the alkaline Guernsey soil was lower than that of the applied mine water (100 percent removal), whereas the copper concentration for the Rayne effluent was nearly twice as great. Removal rates for copper are also pH dependent. Copper will precipitate as a carbonate or hydroxide at high pH (Krauskopf, 1972). Beers et al. (1974) conclude that both copper precipitation and possibly absorption reduce copper concentrations in higher pH Guernsey soils (pH around 8); but copper was extracted from the Rayne soil which had a pH range of about 4 during the experiment (Figure 47).

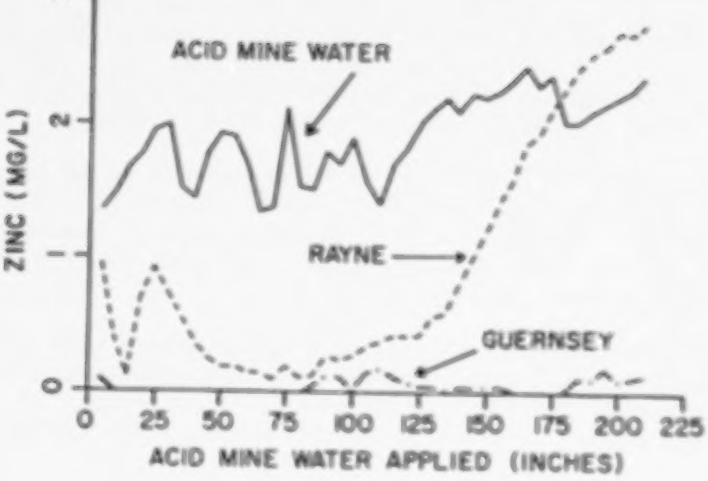


Figure 46. Zinc content of acid mine water and Guernsey and Rayne soil column effluents (Source: Beers et al., 1974).

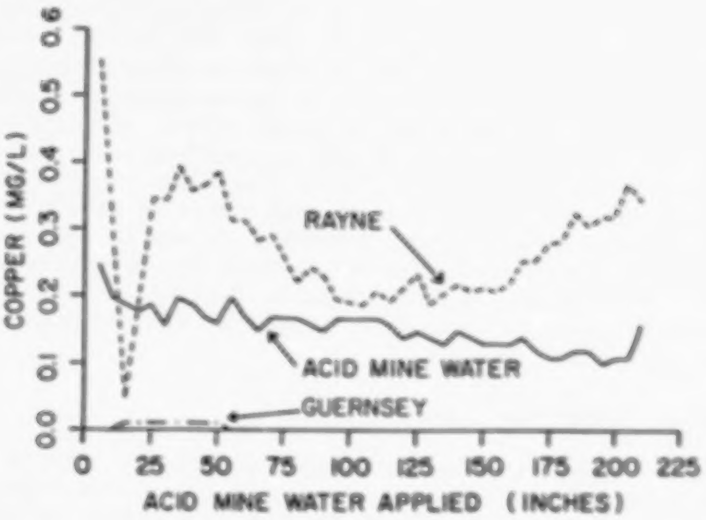


Figure 47. Copper content of acid mine water and Guernsey and Rayne soil column effluents (Source: Beers et al., 1974).

Beers et al. (1974) found that the potassium content of the acid water was decreased by the Guernsey soil for all acid mine water applications, whereas it was decreased only slightly or not at all by the Rayne soil during the first three quarters of the study. Later in the study, the potassium content of Rayne effluent exceeded that of the applied mine water, indicating that potassium was being leached from the soil. The Rayne soil absorbed less than the Guernsey because of its smaller cation exchange capacity and greater competition of H+ and Al for these exchange sites (Figure 48).

Magnesium was retained by both soils at first, but at decreasing rates. The trend continued for the Rayne soil after 318 cm (125 in) of mine water had been applied, whereas the Guernsey soil showed a greater magnesium content later in the study. By the time 457 cm (180 in) had been applied, both soils lost their magnesium retention capacity.

Calcium concentrations also increased in both effluents with time, until they exceeded applied concentrations (Figure 49). This suggests that calcium ions were being replaced by hydrogen as well as other ions from the exchange complex and by a dissolution of $CaCO_3$ from the Guernsey soils (Beers et al., 1974).

These studies together with other field observations and theory reveal that natural soil and rock materials can cause a lag in the migration of dissolved mineral constituents derived from acid mine drainage. The magnitude of the lag depends on the physical and chemical properties of the soil and rock involved. In general, the higher the soil pH, the greater is the tendency for these constituents to be retained within soil and rock. Absorption processes in general will provide less protection against pollution than precipitation reactions, because the exchange sites are finite. Once these sites are filled, pollutants will continue to migrate within the exchange media. Furthermore, as the soil pH drops, some constituents absorbed previously can be leached from the exchange media and others stripped from soil and rock particles for the first time and enriched within the water in concentrations greater than before. Precipitation reactions, on the other hand, can account for the prolonged attenuation of pollutants as precipitates accumulate in soil and rock. But again, favorable pH and Eh conditions must be maintained to sustain these reactions and prevent the redissolution of these precipitates. Application of lime would be required to maintain soil pH conditions if soils are to be routinely flooded or irrigated as a means of treating acid mine drainage.

Application of Sewage Sludge and Effluents

Sewage sludge and effluents are alternative sources of nutrients that provide both organic matter and moisture if used in the liquid form. Demonstration studies at The Pennsylvania State University, Fulton County, Illinois, and elsewhere reveal that repeated applications of sewage sludge over at least one growing season will greatly stimulate plant growth, including grasses, evergreens, and deciduous trees.

Prior attempts at revegetating highly acid spoils in Pennsylvania, Maryland, West Virginia and other selected mining areas in the eastern district have been unsuccessful because of high acidity, toxic levels of iron,

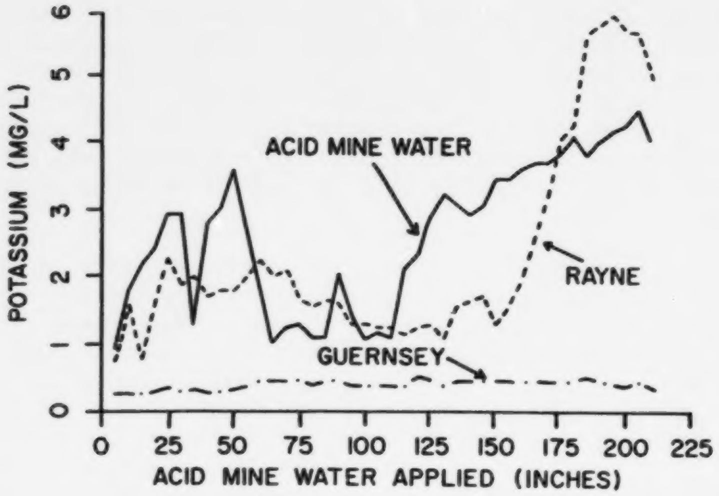


Figure 48. Potassium content of acid mine drainage and Guernsey and Rayne soil column effluents (Source: Beers et al., 1974).

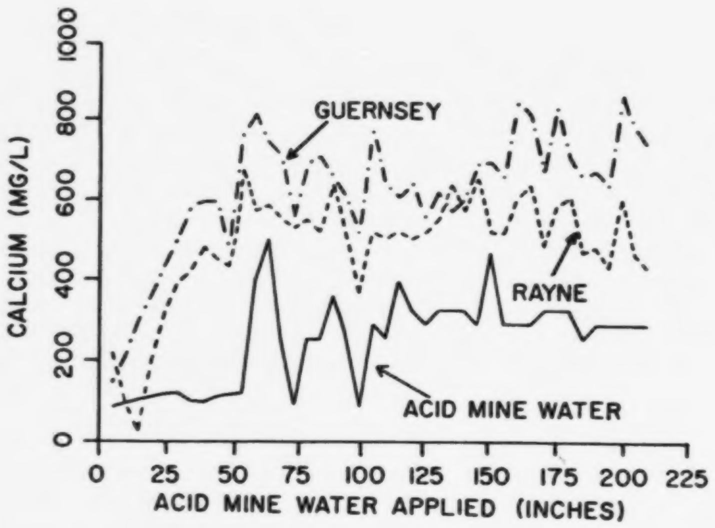


Figure 49. Calcium content of acid mine drainage and Guernsey and Rayne soil column effluents (Source: Beers et al., 1974).

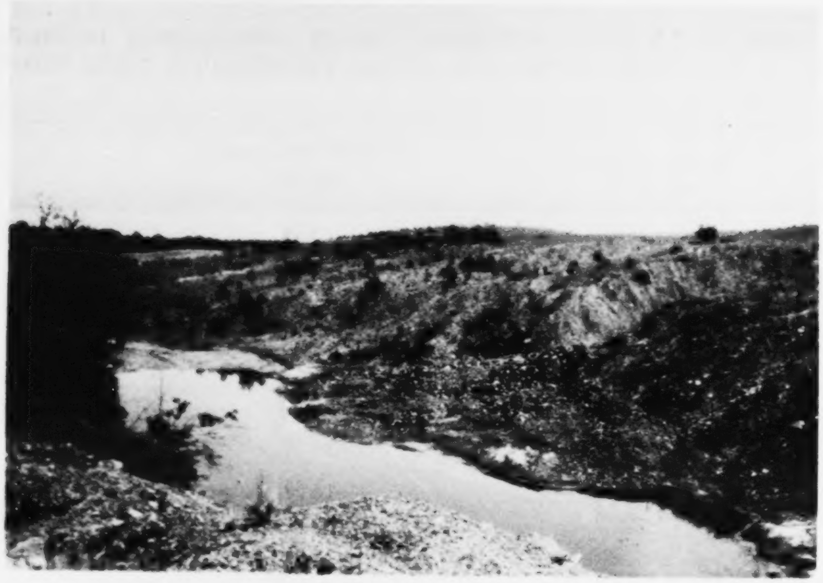
aluminum, and manganese, low moisture content, and extremely high summer surface temperatures (Sopper et al., 1970). These investigators conclude that treatment with sewage effluent and liquid digested sludge will ameliorate these conditions (see Figure 50). The slightly alkaline, nutrient-enriched wastewater can leach acids and toxicants below plant root depth and provide organic colloids to detoxify the soluble iron, aluminum, and manganese. Wastewater and sludge also provide the necessary moisture for vegetation survival and growth. Evaporational cooling also reduces lethal surface temperatures of mine spoil, which helps plants gain a roothold in an otherwise hostile environment.

Table 10 gives the average concentrations of constituents in the sewage effluent and sludge used during the first 2 years of the Penn State Univ. demonstration project. Soils used in large bin experiments were extremely acid (pH 2.0 to 3.0) and remained barren despite 23 years of exposure and several attempts at revegetation (Sopper et al., 1970). Table 11 shows the wastewater and sludge irrigation schedule used in their study and the fertilizer equivalents applied through effluent and sludge treatments.

Tree seedlings were selected according to types that might be used in mine reforestation work, and these showed a high percentage of survival following 24 weeks of weekly sludge and effluent applications (Table 12). Growth of surviving seedlings was noteworthy following a single growing season and irrigation schedule (Table 13). Grass and legume growth response were also highly significant. No seedlings in control boxes survived the 2-year study, whereas a lush growth was obtained for samples receiving a combined application of 5 cm (2 in) of effluent and 5 cm (2 in) of sludge on a weekly basis.

These demonstration studies also revealed that effluent samples obtained 1.2 m (3.5 ft) below the spoil surface showed improvement in quality when compared to control plots (Tables 14 and 15). Sopper et al. (1970) indicate that the pH of percolate obtained in control boxes receiving natural rainfall ranged from 2.2 to 3.8 before irrigation treatment, which was well below the toxic range. During 24 weeks of irrigation, pH increased to 4.06, whereas other ions (K, Ca, Mg, Na, Zn, Cu and B) remained higher in the control bins than in the treated bins. The higher concentrations appear to be the result of solubilization of native rock by the high acidity of soil water in the control bins. Irrigation with effluents and sludge leached and diluted the native salts, and the solubilities of the manganese, iron, aluminum, copper, and zinc were suppressed by the dual action of the effluent and sludge alkalinity and the humic precipitation of organic sludge colloids (Sopper et al., 1970).

These and more recent findings indicate that more toxic mine spoil can be revegetated, and thereby benefit water quality, by using land applications of municipal sewage effluent and sludge. The long-term water quality benefits that may result after effluent and sludge applications are terminated are not as well documented. However, interception, evapotranspiration, and oxygen uptake in the shallow root zone will all be increased following revegetation, and side benefits of water quality improvement are anticipated. This latter point needs more detailed verification through actual field demonstrations.



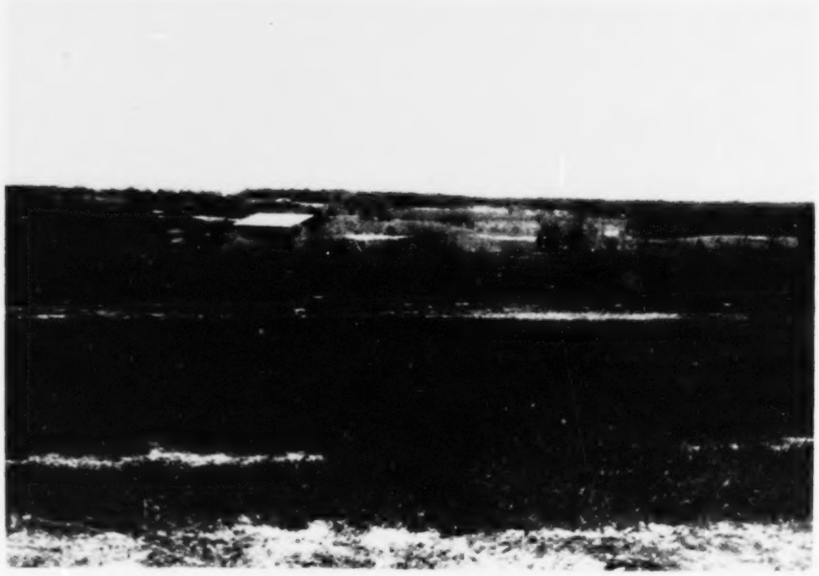


Figure 50. Barren, acid-producing spoil that fails to support vegetation (top), and revegetation of the same spoil following treatment by sewage sludge (bottom). Palzo Project, Southern Illinois.

TABLE 10. AVERAGE CONCENTRATIONS OF CONSTITUENTS IN THE SEWAGE EFFLUENT AND SLUDGE USED IN THE PENNSYLVANIA STATE DEMONSTRATION PROJECT[*]

Constituent	Sewage effluent (mg/ℓ)	Sludge (mg/ℓ)
pH	7.2	7.6
Org-N[†]	34.4	932
NO_3-N	6.1	---
P	5.24[‡]	125[#]
K	13.7	79.6
Ca	34.9	136.5
Mg	16.0	33.8
Na	35.2	33.8
Mn	0.04	1.30
Fe	0.50	14.80
Al	0.90	57.5
Cu	0.17	1.40
Zn	0.11	1.80
B	0.36	0.40
Dry solids	---	3200

[*] Source: Sopper et al., 1970.
[†] Includes NH_4-N.
[‡] Soluble orthophosphate.
[#] Total phosphorus.

TABLE 11. FERTILIZER EQUIVALENTS OF EFFLUENT AND SLUDGE TREATMENTS[*]

Treatment	Amount applied (lb/acre)	Fertilizer equivalent (lb/acre)		
		N	P_2O_5	K_2O
2 in. effluent	2,000	19	6	8
1 in. effluent and 1 in. sludge	9,980	46	13	6
2 in. effluent and 2 in. sludge	12,469	64	17.6	8
2 in. sludge	11,429	66.5	18.4	7

[*] Source: Sopper et al., 1970.

Footnote: 1 lb = 0.373 kilograms.
1 acre = 0.405 hectares.

TABLE 12. TREE SEEDLING SURVIVAL RATES* (IN %)

Species	Control	Treatments				Mean
		2E	1E+1S	2E+2S	2S	(5% Sig.)
Japanese larch	0	2.5	0	0	0	0.5a†
White spruce	0	40	10	7.5	0	11.5ab
Norway spruce	0	35	2.5	2.5	2.5	8.5ab
White pine	0	62.5	20	12.5	0	19b
European alder	0	37.5	37.5	27.5	2.5	21b
Hybrid poplar	0	10	2.5	10	10	6.5ab
Black locust	0	65	82.5	85	67.5	60c
Mean (1% sig.)	0a	36c	22bc	21bc	11ab	---

*Source: Sopper et al., 1970.
†Duncan's mean separation.

Note: E = Municipal sewage effluent.
S = Municipal sewage sludge.

TABLE 13. AVERAGE HEIGHT GROWTH OF SURVIVING TREE SEEDLINGS* (IN INCHES)

Species	Control	Treatments			
		2E	1E+1S	2E+2S	2S
Japanese larch	0†	0	0	0	0
White pine	0	2.0	1.4	3.0	0
Norway spruce	0	2.1	2.0	1.9	2.3
White spruce	0	2.2	2.1	1.7	0
European alder	0	6.0	3.5	2.7	1.6
Hybrid poplar	0	13.8	0	14.4	11.1
Black locust	0	4.3	12.8	13.7	9.9
Mean	0	4.0	3.1	5.3	3.6

*Source: Sopper et al., 1970
†No surviving seedlings.

TABLE 14. AVERAGE EFFLUENT CONCENTRATIONS OF pH, Fe, and Al* (mg/ℓ)

Treatment	pH†		Fe‡		Al‡	
	A	B	A	B	A	B
Control	2.20	2.18a	1162+	126+	477	248+
2E	2.58	2.61bc	147	21	275	57
1E+1S	2.43	2.44ab	446+	61	544	79
2E+2S	2.75	4.06d	67	2	165	3
2S	2.80	2.86c	117	29	355	61

*Source: Sopper et al., 1970.
†A is pretreatment period; B is treatment period.
‡A is average for first 8 weeks and B is average for third 8 weeks.

Note: E = Municipal sewage effluent.
S = Municipal sewage sludge.

TABLE 15. AVERAGE EFFLUENT CONCENTRATIONS OF P, NO_3-N, Org-N, K, Ca, Mg, Na, and Mn* (mg/ℓ)

Treatment	P	NO_3-N	Org-N†	K	Ca	Mg	Na	Mn
Control	0.029	<1.0	---	108.7	44.9	115.8	0.5	50.4
2E	0.086	4.8	7.6	20.4	16.7	32.8	15.4	15.4
1E+1S	0.126	14.4	47.8	22.9	31.5	65.8	13.2	26.8
2E+2S	0.149	50.4	105.6	18.8	41.3	31.5	18.7	9.6
2S	0.160	41.1	105.7	27.3	60.5	72.0	18.1	29.4

*Sopper et al., 1970.
†Includes annomiacal nitrogen.

In more arid regions, the benefits of sewage effluent and sludge treatment may be less permanent once the application of sludge and/or effluent is terminated. Capillary effects within the soil can cause the migration of acidic soil moisture back to the land surface, and a slow reversal in benefits probably will occur as the buffering capacity of this shallow treatment zone is depleted.

Some short-term improvements in water quality should be expected from the application of alkaline sewage sludge to spoil banks. However, the main impact of using limited amounts of sewage sludge, either in liquid or dried form, will result from the increased plant responses and evapotranspiration losses of surface and soil moisture. Other soil additives, namely a disseminated mixture of limestone and mulch, should be considered to bring about maximum and prolonged beneficial results in abating pollution from strip mine spoils.

Use of Limestone Barriers

Water quality can be improved within springs and streams using limestone barriers placed within the spring or creek. Rather ideal field conditions must be met for this mine drainage pollution abatement technique to apply. The barrier should contain rather pure limestone that will react with acidic drainage, and grain sizes should be selected to provide a high surface area and at the same time allow for sufficient leakage to preclude erosion of the leaky barrier by flood flows. Furthermore, dissolved iron concentrations must be relatively low to preclude the armoring of limestone fragments in the barrier by iron precipitates.

Theoretical calculations by Pearson and McDonald (1975) previously showed that the pH adjustments that can be achieved within the barriers depend on many factors, including:

1. Grain size and purity of barrier material used.
2. Velocity of flow through the barrier, or contact time between the limestone and acidic drainage.
3. Iron content of water being neutralized.

Study of the theory involved (which must still be tested under various streamflow and water quality conditions to determine its full utility) shows that a buffer capacity can be added to the stream directly to raise the pH and reduce the acidity flux of surface water directed through the barrier.

A major constraint to the application of this abatement method is posed by the infiltration capacity of the barrier. A high permeability will result in rapid throughflow and limited treatment. Finer-grained barrier deposits can result in the frequent plugging of the barrier face and frequent overtopping of the barrier by flood waters, again with little benefit of treatment. Sediment, organic matter, and precipitates in suspension will quickly form a filter cake on the upstream face of the barrier, thereby reducing its effectiveness. The method appears to apply best to constant flows of rather favorable quality. Thus excess flood waters may have to be passed around the barrier, or the structure may have to be placed so as to tap and treat a portion of the base flow following siltation and iron removal.

Equations 5 through 8 of this report show that the pH of acid water can be raised by simple dilution and buffering when it is mixed with water containing bicarbonate. Bicarbonate-enriched water is more efficient in neutralizing acidic water than a simple mixing of bicarbonate-free water with acid water of a lower pH (equation 4).

Pure calcite ($CaCO_3$) could be expected to raise the pH of pure rain water to 8.3 given a prolonged contact time. However, this represents a laboratory idealization that rarely can be met under field circumstances.

Construction of a Test Barrier--

Spring 004 on Jonathan Run, Centre County, Pennsylvania, was selected for a brief field experiment using the limestone barrier method. This spring was being monitored for water quality responses resulting from a limestone/limeplant flue dust method of acid drainage reduction described previously (Waddell et al., 1979).

Various codes of crushed limestone aggregate (Table 16) supplied by Marblehead Limestone Company, Pleasant Gap, Pennsylvania, were subjected to laboratory permeability tests by Herman (1977) to select an aggregate of fine grain size but of sufficient permeability to accommodate a portion of or all of Spring 004 flows. Several years of gaging record were available and guided the selection of the aggregate.

A 20-ton, Code 72 Valentine limestone barrier was first placed below the spring on May 20, 1977; but the permeability and cross-sectional area of the barrier were insufficient to allow the full discharge of the spring to flow through the barrier. Erosion of barrier deposits during construction increased the length of deposit through which flow had to take place. A clay dike had to be built to force the water through the barrier. Because of budget constraints, insufficient clay was available to raise this dike to the necessary level. A significant portion of the flow topped the dike, bypassed the barrier, and hence was not neutralized.

On May 29, 1977, an additional 20 tons of Valentine limestone were added to the barrier, and the dike was raised to increase the upstream pool elevation and hydraulic gradient within the barrier. Eventually this barrier was also breached by high flows. Ideal conditions will be achieved when the entire water flow from Spring 004 passes through the limestone barrier and only peak flows are allowed to bypass it. Some leakage from the original pool floor and sides has probably occurred and bypassed the barrier as well. But a more serious problem has resulted from selection of a too fine grain size. As spring flow increased, some water bypassed the barrier by entering a spillway in the dike provided to protect the dike and barrier against erosion by flood waters. Eventually, the barrier was again topped, despite repeated attempts to repair the barrier. A more elaborate design and construction project should eliminate this difficulty.

TABLE 16. GRAIN-SIZE DISTRIBUTION FOR THREE CODES OF VALENTINE LIMESTONE PROVIDED BY THE MARBLEHEAD LIMESTONE COMPANY*

Code of limestone	Screen size		Passing
	Number	Inch	%
Code 55 Stone			
(3/8" x 0")	3/8"	0.375	98.94
	#4	0.185	70.48
	#8	0.093	44.43
	#16	0.046	26.79
	#30	0.023	16.52
	#50	0.012	10.26
	#100	0.006	5.97
	#200	0.003	1.35
Code 60 stone			
(1/4" x 0")	1/4"	0.250	99.58
	1/8"	0.125	77.99
	#8	0.093	65.25
	#16	0.046	36.65
	#20	0.033	26.34
	#30	0.023	21.90
	#50	0.012	11.13
	#100	0.006	5.61
	#200	0.003	1.16
Code 72 stone			
(1/4" x 20 mesh)	1/4"	0.250	96.68
	#4	0.185	92.63
	#6	0.131	85.64
	#8	0.093	66.63
	#12	0.065	38.56
	#16	0.046	16.61
	#20	0.033	5.74

* From J. Herman in Waddell et al., 1979.

The erosion problem became more serious as time passed and as suspended organic matter filtered out on the upstream face of the barrier, thereby reducing its infiltration rate and permeability. Only a few tenths-of-meter separated the barrier from the spring outlet. An algae mat also developed on the face of the barrier, further reducing its permeability. A favorable infiltration rate probably can be maintained by increasing the grain size, and hence the permeability, of the barrier. This project can be done in stages so that the upper section of the barrier is most permeable, with the lower section containing the finer-grained aggregate. Flood flows should be accommodated in this way by the barrier, and low flows should be channeled through the finer-grained portions of the barrier (Waddell et al., 1979).

Early chemical data obtained above and below the barrier were encouraging and revealed that a very favorable rise in pH and bicarbonate was being achieved by the barrier gravels selected (Table 17). Their high surface area, purity, and the prolonged contact time with the water are beneficial to the neutralization reactions.

Immediate results were determined by J. Herman (1977). The pH was measured the same day the barrier was constructed. For water just above the barrier, pH was 4.90, and for water flowing out of the toe of the barrier, pH was 7.75. Water sampling was done at sites in the stream above and below the barrier at different points 1 and 2 weeks after the barrier was constructed (see Table 17).

Field demonstrations are justified for this instream pollution abatement technique. It may be difficult to treat major streams using this procedure, but at least it may be possible to channel portions of streams through such barriers to allow reduction of iron and sediment.

PHYSICAL FIELD METHODS

Three methods are reported under this grouping: the development of water storage areas in lieu of direct release, the use of connector wells to control potable groundwater, and the use of connector wells to dispose of polluted groundwater.

Development of Water Storage Areas in Lieu of Direct Release

In some situations, the development of permanent water storage areas may be preferred over the direct release of the mine waters to the watershed during reclamation. These conditions must become part of the original mine plan and be approved by the appropriate government regulatory bodies with the consent of the landowner. The objectives normally incorporate the creation of recreational lakes, planned community developments (including golf courses), or water sources for agricultural purposes (cattle, irrigation, etc.).

The conditions favorable to such planning include the availability of an adequate water source (quantity and quality), appropriate geohydrological conditions (water table levels), and natural terrain features (especially

TABLE 17. CHEMICAL WATER QUALITY DATA OBTAINED ABOVE AND BELOW THE LIMESTONE BARRIER*

Sampling time and site	pH	Specific conductivity (micromhos)	Bicarbonate (mg/ℓ)
Average from weekly readings for April:			
021: the spring	4.77	155	2.24
022: stream, where head of barrier is now	4.90	162	0.75
023: stream, where toe of barrier is now	5.07	164	2.99
024: stream, where it flows into the lake	4.95	159	1.12
One week after the barrier:			
021	---	---	---
022	4.44	150	---
023	7.74	250	---
024	4.39	163	---
Two weeks after the barrier:			
021	5.00	138	2.24
022	4.92	149	1.12
023	7.87	253	59.36
024	4.45	---	0

* From J. Herman in Waddell et al, 1979.

elevation). In general, the available water quality must be satisfactory or provision must be made for continuous treatment. The ponding of waters may reduce degradation of water quality through reduced exposure to mineral surfaces, strata coverage, reduced oxygen availability, the presence of calcareous strata, or controlled water quality planning.

Among the planning requirements are a detailed knowledge of the local terrain, geology, geohydrology, stratigraphy, water quality, and limnology, as previously described. Provision must be made to ensure the water-holding capacity of the ponded area; evidence must be presented that the water quality can be satisfactorily maintained; provision must be made for the 10-year, 24-h precipitation event (including spillways, provision against localized erosion, and maintenance of terrain stability) and physical stability must be provided for any man-made dam structure.

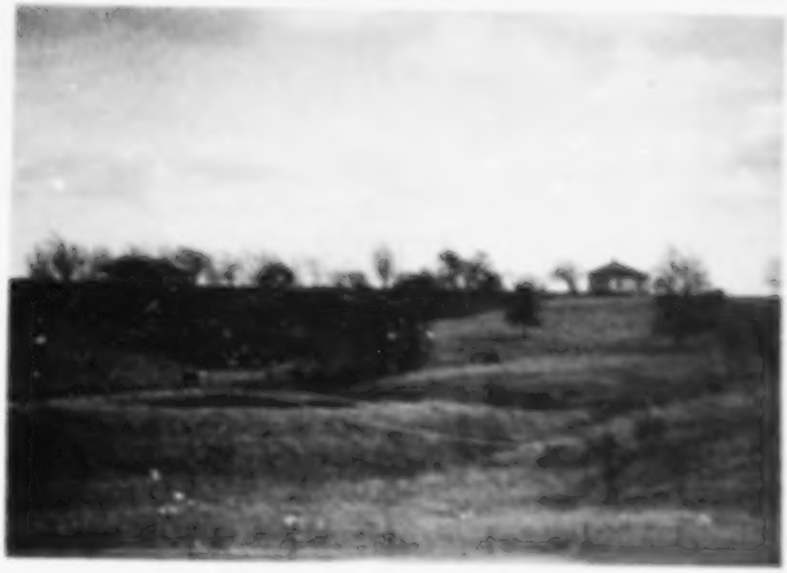
Several permanent water storage areas have been developed, and others are planned. In Somerset County, Pennsylvania, a newly initiated coal surface mine operation is destined to become an elaborately planned housing development, centering around a large, freshwater lake fed by surface and underground water sources encompassing the disturbed area. In Oklahoma coal mining districts, where precipitation levels are low, reclaimed areas are planned to develop small, shallow ponds to provide drinking water for cattle. The slopes are stabilized, vegetated to control erosion, and contoured to provide safe access for large animals (Figure 51).

Other documented examples are: (1) The Elcampton project in Clearfield County, Pennsylvania, where a large pond holds drainage from an abandoned surface mine to observe and hopefully improve water quality (little change has been reported), and (2) The Sheban project (perhaps the most publicized effort) in eastern Ohio in 1965 (Hall, 1965). In the latter project, permeability occurred through the impacted spoil, producing unacceptable effluents. Over the years, the effluent quality has improved, but the approach, without modification, would not meet current regulations. Other studies are documented by Riley (1965) and Campbell et al. (1965).

Use of Connector Wells to Control Groundwater

Applications--

Connector wells or gravity wells (Parizek, 1971; Parizek and Tarr, 1972; Parizek, 1974) could be used to reduce the volume of water that comes into contact with rocks disturbed by mining in several ways. Connector wells have their best potential, under favorable conditions, in controlling leakage into deep mines. They may also be used in strip mining regions under restricted conditions to reduce the amount of groundwater that enters strip mine spoil and auger holes from highwalls, unmined coal, and truncated aquifers (Figure 52). Where strip mines collar hill sides or are located in recharged areas, but uplands are still intact and are underlaid by productive aquifers that are located above the coal bed, connector wells should be beneficial in diverting groundwater from spoil banks before it becomes contaminated (Figure 52). The connector well concept is predicated on the assumption that a significant reduction in water entering either deep mines or spoil banks will result in a reduction in the volume of mine drainage



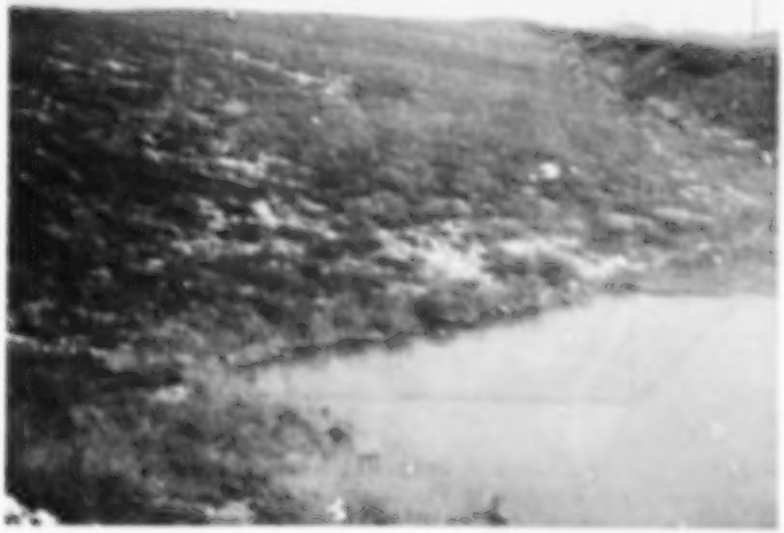
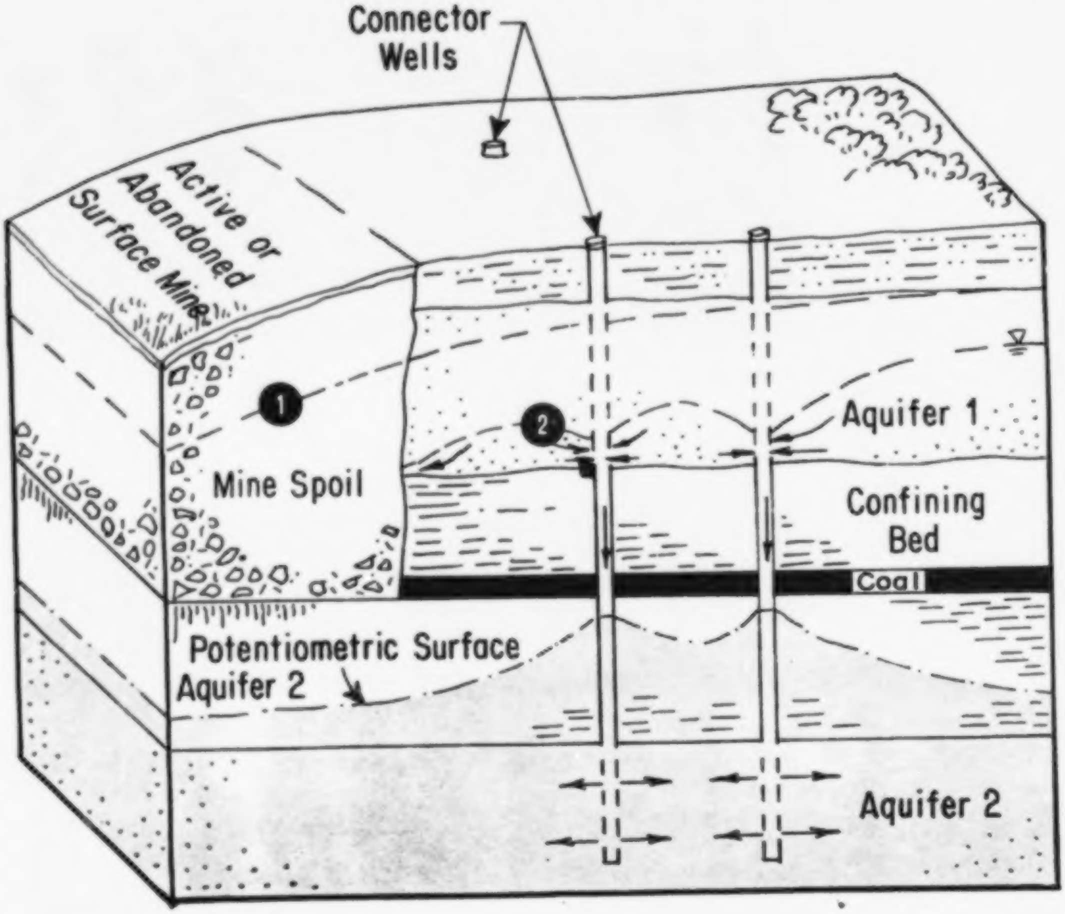


Figure 51. Reclaimed surface mine with vegetated area and contouring to provide safe pond slopes for large animals.


Connector Wells
Active or Abandoned Surface Mine
1
2
Aquifer 1
Mine Spoil
Confining Bed
Coal
Potentiometric Surface Aquifer 2
Aquifer 2

1 = Original water table configuration
2 = Final water table configuration

Figure 52. Connector wells used to reduce inflow of groundwater to surface mines.

produced and a reduction in the total pollution load contained in the drainage. This is the principal objective of the demonstration project designed by Parizek (1974)--namely, to document the extent to which the pollution load will be reduced by the use of gravity connector wells. A feasibility study has been conducted by Schubert (1978) that shows the amount of groundwater that might be intercepted by connector wells under one set of hydrogeological conditions in central Pennsylvania.

For a connector well method to be effective, several hydrogeologic requirements must be satisfied:

1. A relatively productive aquifer should underlie a hilltop or upland that has not been completely strip mined. This may be sandstone, siltstone, or even the remaining coal bed, outwash sand and gravel, or other unconsolidated deposits. Or if other coal seams in the hilltop have been mined, mine water should be of good quality and connector wells should be used to prevent groundwater inflow to strip mines lower on the slope that are likely to produce mine drainage of poor quality.
2. The upper aquifer should still contain an appreciable quantity of groundwater despite the strip mine developed around or along the hill, and groundwater should discharge from the aquifer through the highwall to the strip mine environment. This need not be true for many strip mines in the eastern coalfields where the truncated aquifer may be essentially dewatered.
3. A deep sandstone or rather permeable aquifer should underlie the hill that has a potentiometric surface that is lower in elevation than that of the overlying aquifer.
4. Zones of fracture concentration within bed rock revealed by fracture traces and lineaments should be recognizable within the upland. Intersecting zones of fracture concentration should be used to locate gravity connector wells with maximum yields and with maximum recharge rates. Only a few highly efficient wells will be required to drain potable water from the overlying aquifers compared to the number that might be required if drilling were done on a grid.
5. The quality of groundwater for the shallow source bed and deep aquifer should be compatible to prevent the plugging of the well bore and aquifer by iron and/or other precipitates.
6. The coal remaining beneath the upland aquifer should not be slated for mining in the near future unless the benefits derived from the connector wells exceed the costs.

Desirable aspects of this abatement scheme are that (1) the dewatering system will work by gravity for an indefinite period, (2) it salvages potable groundwater than can be reclaimed for later use either from the shallow source bed or deep aquifer being recharged, and (3) the method should be relatively inexpensive under appropriate field conditions. Aquifers containing potable groundwater should not be polluted by this abatement technique, provided that connector wells are properly designed (Parizek and Tarr, 1972; Parizek, 1974).

Evaluation Technique--

The presence of relatively productive aquifers beneath hilltops must be established for each mine within a given watershed. Isolated hilltops and uplands not likely to be stripped in the future but already stripped along the crop can be examined for their stratigraphy, structure, aquifer potential, etc. If highwalls are no longer available for study, fracture trace mapping, test drilling, and pumping test programs can be conducted to define the hydrogeologic setting. One to two test holes per mine site may be all that are required to evaluate the suitability of the method.

The presence and favorable head relationship for the deep aquifer system should be established during the same drilling program. Water samples can be obtained from both aquifers to establish their chemical compatibility. If precipitation reactions are inevitable near the well bore, maintenance and rehabilitation costs may prove to be excessive in order to maintain favorable recharge rates for the lower aquifer.

The use of connector wells to control potable groundwater should be applicable within some watersheds, where it will provide at least some local relief. But the method will be limited in use to unmined and mined upland settings where it is difficult to prevent groundwater contact with spoil deposits using other techniques, and where highwall seepage volumes are appreciable. Grading and channeling to promote runoff across mined out and restored intervals from these uplands will help to reduce the pollution load, but these practices alone will not eliminate groundwater flow to spoil deposits. A line of connector wells placed parallel to the former highwall, on the other hand, may prove to be a highly effective pollution abatement procedure.

Use of Connector Wells to Dispose of Polluted Groundwater

Applications--

Aquifers beneath strip mines and possible deep mines in selected watersheds have been polluted by coal mine drainage in a number of locations. Hillside discharges of acid mine drainage located below mined-out coal beds and controlled by zones of fracture concentration, stratigraphic sequence, and colluvial and alluvial confining beds and polluted flowing wells reveal that this is the case. An alternative connector well abatement scheme to reduce pollution within selected upland tributaries is possible.

Polluted water contained within aquifers beneath mines might be drained by gravity into deep confined aquifers that provide avenues for regional groundwater movement and within aquifer neutralization. This abatement procedure should be considered only if one of the following criteria is met:

1. The deep aquifers are confined and contain brines or other poor quality water and hence will not be adversely polluted in the process;
2. The deep aquifers contain sufficient alkalinity to neutralize acid mine water intentionally recharged to the aquifers;

3. The deep aquifers are already extensively polluted by mine drainage beneath the watershed, but groundwater flow is such as to favor the subsurface transport of this drainage to adjacent regions where alkalinity is available to bring about complete neutralization. Neutralization should be complete before this mine water is again discharged to land surface along major river valleys. By this scheme, the aquifer system may be used as a "pipeline" for transmitting polluted mine drainage to points of treatment within the aquifer or to polluted aquifers where it is desirable to maintain or re-establish water quality in the smaller watershed to protect an existing public water supply or other important water use. The following example is offered to illustrate the concept.

Example--

The mountaintop Burgoon Sandstone is believed to underlie Licking Creek watershed in Clarion County, Pennsylvania. It is the shallowest possible candidate aquifer that could be used in such a scheme. However, water quality conditions have not yet been adequately defined for this aquifer system to establish which of the three possibilities listed above might apply. Preliminary data collected by U.S. Geological Survey personnel working in the Clarion River drainage basin suggest that portions of this aquifer system indeed contain brine or brackish groundwater and some alkalinity. Alkalinity may be derived from the overlying Vanport limestone and calcareous shales where they are well developed and where groundwater flows through these calcareous deposits and into the deep sandstone (Figure 53). The alkalinity source may be located either in Licking Creek or in adjacent watersheds. In either case, neutralization of mine drainage should result within the deep aquifer system as long as the two waters are mixed before being discharged to the Clarion River. Neutralization reactions accompanying groundwater flow result in hard, sulfate-enriched waters with favorable pH. Iron may precipitate out on joint and mineral grain surfaces.

Of the three cases listed above, items 2 and 3 are more likely to apply for the Licking Creek region. The principal benefit would be a reduction in the pollution load of Licking Creek, a tributary of the Clarion River. However, for this hypothetical example, no public water supplies are developed from Licking Creek; hence more general water quality improvements resulting within the creek may not justify the possible pollution damage that may be caused within portions of the local deep aquifer system using such a connector well system.

This abatement scheme differs from the one where water is made to bypass the mine environment, in that acid mine drainage already produced would be fed by gravity into underlying aquifers either for storage or treatment (Figure 53). The prolonged success of the method would be insured if neutralization could be relied on within the aquifer rather than around the connector well bore. Iron would have to be kept in solution during the drainage and recharge process until alkaline and acid water were mixed within the confined aquifer some distance from the connector well. Natural alkalinity and buffer capacity contained within a segment of the flow system may be added to the deep aquifer somewhat distant from the connector well locations.

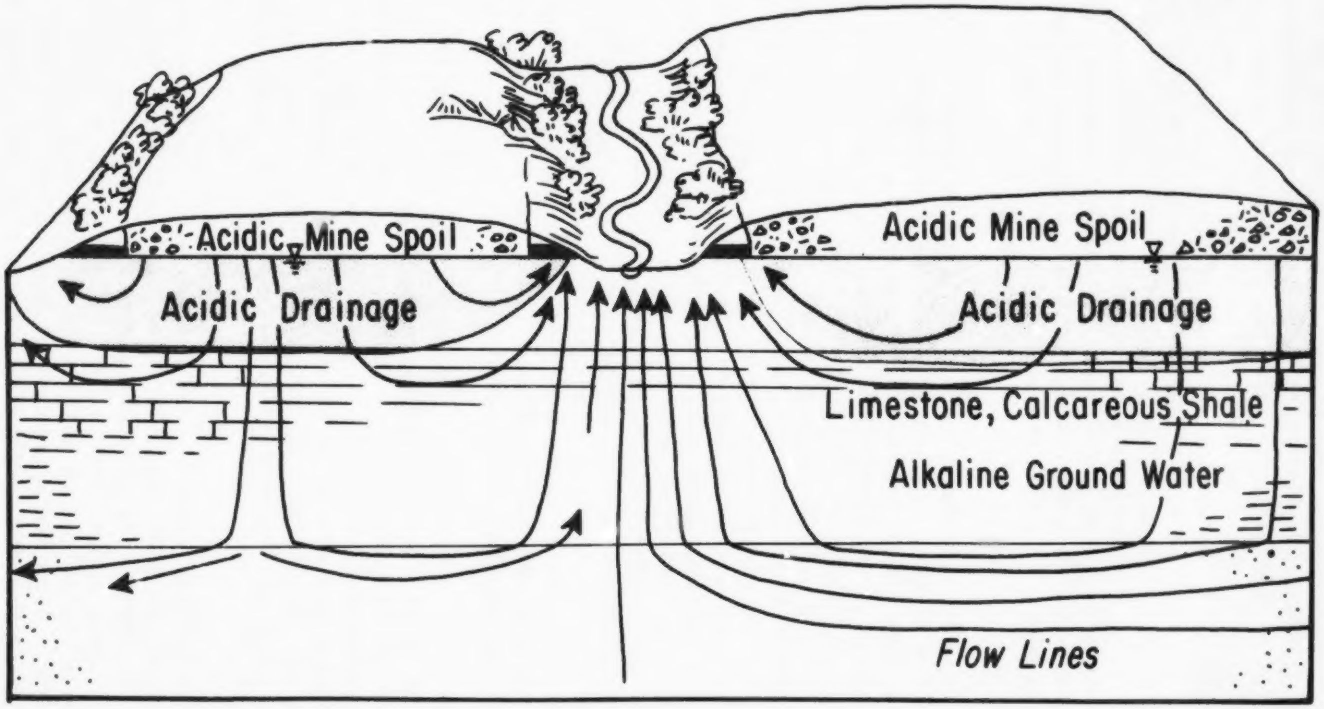

Acidic Mine Spoil
Acidic Drainage
Acidic Mine Spoil
Acidic Drainage
Limestone, Calcareous Shale
Alkaline Ground Water
Flow Lines

Figure 53. Alkaline groundwater contained in deep aquifers underlying acid-mine-drainage-producing mines lacking other sources of alkalinity.

Byproducts of acid neutralization (SO_4, etc.) would still be maintained in solution and eventually be discharged from the aquifer system; but acidity, iron, and other mineral species precipitated as a result of the neutralization process would be retained within the aquifer. If carefully programmed in advance, long-term reduction of aquifer permeabilities might be insignificant, but a significant and long-term water quality improvement might be achieved within selected watersheds where no other pollution abatement procedure is economically feasible.

Evaluation Technique--

To exploit such deep flow systems, the aquifer system would have to be investigated in some detail to establish regional patterns of flow and regional water quality variations within the deep aquifer. Both a productive sandstone beneath the strip mine (the source bed containing acid mine drainage) and a deep aquifer must be present, and both must have favorable head and yield characteristics, as were required for the other system described above. Water qualities must be compatible at least near the connector wells to avoid the rapid plugging of the borehole-aquifer interface by iron and other precipitates. And ideally, the deep aquifer should contain alkaline groundwater entrained within the flow system from an adjacent region, or derived locally from the deep aquifer. Alkalinity may be derived either from well-developed limestone, calcareous shales and glacial drift located above the deep aquifer in its recharge area, or from calcareous rocks, located below the deep aquifer where the direction of groundwater flow is upward.

A regional groundwater study would be required to define such hydrological and geochemical systems. The aquifer thickness, distribution, potentiometric surfaces, and water quality would have to be established within and beyond the bounds of individual mines and tributary watersheds. A carefully designed test drilling program might also be required to define aquifer hydraulic properties and reliable head and groundwater quality data.

The benefits of this untested, natural abatement system could be far-reaching if the pollution load could be removed at favorable locations within selected watersheds on a permanent basis and at minimal costs. Byproducts of neutralization would be stored and disposed of in deep aquifers, natural sources of alkalinity would be exploited, and gravity would serve as the power supply! Deep well injection of acid mine drainage as a means of ultimate disposal appears to have severe limitations. The method is not likely to win widespread support, either by the mining industry or by regulatory agencies.

SECTION 6

MONITORING PROGRAMS

INTRODUCTION

Monitoring is required during all phases of mine planning, mining, and restoration. It can include measurements of seasonal changes in groundwater levels, streamflow, and water quality in wells and springs that might be impacted by mining. Erosion, siltation, changes in water levels, etc. can be monitored during site exploration studies, during mining, and following mining. Observation of anomalous behavior of elements of natural systems will reveal the parts of these systems that are incompletely understood. This may justify an expanded exploration program, additional theoretical analyses, or more careful observation.

Abrupt changes in groundwater levels, changes in pumping rates needed to control water, spring and tributary streamflow, and water quality changes should be noted to distinguish perturbations induced by mining from naturally occurring seasonal changes in the system. These changes follow seasonal patterns that are part of a background that must be isolated from impacts on these systems induced by mining. Appropriate detailed records collected by qualified individuals will be useful in protecting mining companies and adjacent landowners alike from litigation. These records will allow for reinvestigation and better definition of elements of the system that do not appear to behave according to initial forecasts. Forecast models thereby can be modified and actual field conditions more adequately defined.

Post-mining monitoring will be resisted by the industry if it feels it will be damaged by long-term, adverse changes in the system shown to be induced by surface mining. However, irrelevant aspects of mining laws that have no bearing on local field circumstances but are required by State and Federal laws can be logically fought when facts are available. Also, the benefits of many mine restoration projects, acid forecasts, erosion forecasts, drawdown forecasts, etc. can be studied and field documented. These data can guide the planning, engineering, and regulation of new mines that will be more in harmony with local circumstances. This can be of benefit to all in the long run and is the only way that an understanding will be gained of the workings of geochemical and hydrogeological systems stressed by surface mining under variable geological, topographical, geochemical, climatic, and mining conditions.

MONITORING WELLS

Selected exploratory borings should be retained for observing water level and water quality changes with season of the year, for noting drawdown following the start of mining, for checking water level responses following backfilling, etc. In many cases, these first-noted changes in water levels or quality can be compared with predicted or computed water level and quality changes determined by analytical or modeling means to see if predicted responses agree with observed responses. Modification in assumed values for recharge, permeability, storage, vertical leakages, etc. can be made in the forecast models so that new water level decline forecasts will be in better agreement with what was observed.

Several State mining laws currently require that all coal test holes be plugged or backfilled immediately following exploration. This backfill requirement is counterproductive to hydrogeological and geochemical monitoring needs and to possible followup hydrogeological investigations. All holes are to be plugged, when in fact, selected borings should be left open to monitor water level changes, conduct pumping tests, observe drawdowns and water quality changes, etc. The value of open test holes should be recognized by regulatory agencies and factored into the design and implementation of mining regulations as well as into mine planning. However, the intent to use these boreholes should be followed up with early action or backfilled if considered of no further value.

Flow net methods of analysis to determine regional or average coefficient of transmissivity values for highwall deposits, for example, can be used to verify permeability data obtained by pumping test or core-testing methods. These tests require the stress of regional cones of pumping depression to acquire suitable data. Also, predicted drawdown values using various analytical methods (i.e., electrical analog models and/or digital models) can be compared with water-level declines actually observed during mining in selected observation wells. Often these comparisons will demand that adjustments be made in estimated values of recharge, coefficients of storage, transmissivity, coefficients of vertical permeability, and other similar hydraulic parameters. Such water-level observation stations can be fitted with continuous water level recorders that require servicing only at monthly intervals or that can be measured on a spot basis at biweekly or monthly intervals using steel tapes or water level probes. It will prove useful to have such observation wells located in important aquifers undergoing development and located between points of water use and the strip mine where mining is planned, in close proximity to public, industrial, and private surface water and groundwater supplies.

Other groundwater monitoring points may prove useful at other locations when establishing the impact that mines are having on groundwater quality in the down-gradient direction of water flow. The quality of mine water actually produced during mining and following surface restoration may be compared with premine forecasts of this quality. Such comparisons will prove useful to regulatory agencies and mining companies alike. For the latter, claims of water quality damage caused by mining can be compared with actual water quality produced within groundwater flow systems adjacent to the mine. Often the first analysis ever conducted on groundwater supplies is done after a mine has been put into operation. Any departure in groundwater quality from ideal, whether natural or man-induced, tends to be blamed on the mine. This problem is best resolved by sampling wells and springs in advance of mining and over a long enough period (6 to 12 months) to define seasonal trends adequately.

Knowledge of groundwater flow systems within the vicinity of surface mines will be required when selecting sites and designing these monitoring wells. At present, most monitoring tends to be confined to obvious surface discharge points related to surface mines and largely ignores the groundwater component of mine discharge that may move laterally or vertically from the mine within soil water and groundwater flow systems. It should be clear that a single monitoring well may be adequate for some mines and entirely inadequate under other circumstances. Monitoring wells should be designed to suit the special circumstances encountered on a mine-by-mine basis.

Figures 54, 55, and 56 show common situations in which monitoring wells fail to detect water quality changes resulting from surface mining. The map view in each figure shows that the direction of groundwater flow is toward monitoring wells placed to intercept mine drainage. However, the cross-sectional views show that flow channels containing groundwater influenced by mining either escape above or below the open end (water-producing part) of the well and hence remain undetected. A simple flow system is shown in each case above, when in actual effect, the stratigraphic sequences for coal measures are far more complicated and will cause complex refractions of flowlines as they travel from beds with one hydraulic conductivity to the next. A single highly conductive or poorly conductive bed only a few meters (or feet) thick can cause an abrupt alteration in the direction of groundwater flow. As a general rule, the position of the mine within a groundwater flow system should be approximately understood--that is, a recharge area, discharge area, or region where groundwater flow is essentially horizontal. Also, surface mines can alter this flow system, as explained in an earlier chapter. These factors should be considered when planning monitoring systems.

Zones of fracture concentrations must also be considered when selecting monitoring well sites completed in bed rock. The more permeable channelways in rock can cause polluted water to bypass monitoring wells (Figure 56), concentrate along zones of fracture concentration, and travel through the rock at a higher velocity when compared to mine water flow in adjacent, less permeable strata. Mine drainage will follow irregular channel ways in the general direction of the regional groundwater flow, but it will follow zones of fracture concentration diagonal to the regional flow pattern.

SOIL WATER

Monitoring of soil water quality poses more difficulty than groundwater. Soil water is in a state of tension and will not migrate into open boreholes under the influence of gravity. Benefits of mine restoration using sewage and sludge applications, limestone aggregates, etc. can be determined by monitoring shallow groundwater within wells, piezometers, springs and seeps,

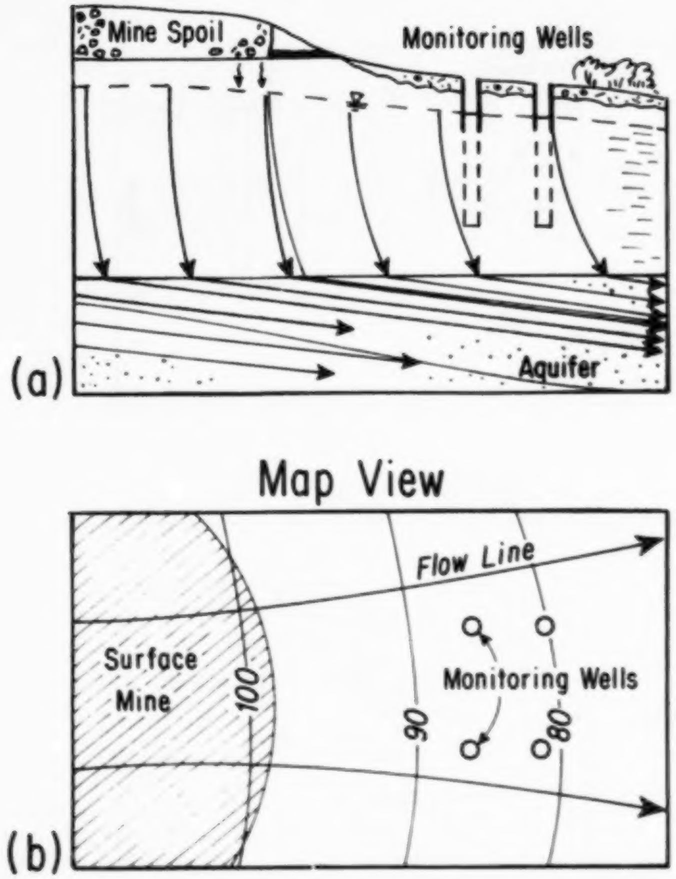
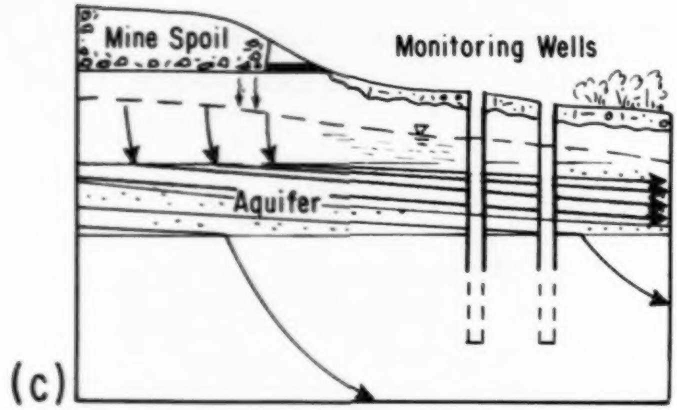

Mine Spoil
Monitoring Wells
Aquifer
(a)
Map View
Flow Line
Surface
Mine
100
90
80
Monitoring Wells
(b)

Figure 54. Monitoring well placed above groundwater flow channels containing mine drainage. Note that flow lines are refracted by changes in rock permeability. In the map view, monitoring wells would appear to be properly located to intercept mine drainage contained in flow channels. (Modified from Parizek, 1973).


Mine Spoil
Monitoring Wells
Aquifer
(c)

Map View

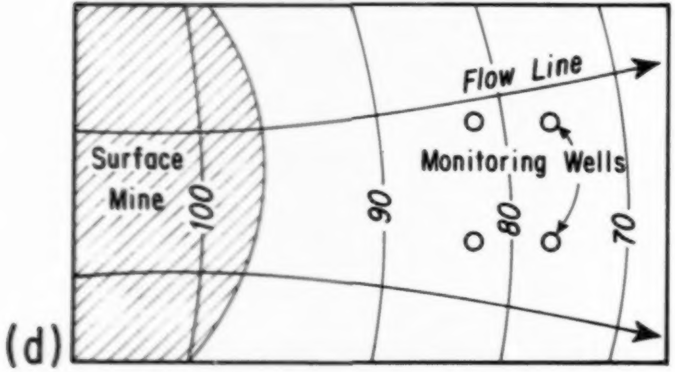

Flow Line
Surface Mine
100
90
80
70
Monitoring Wells
(d)

Figure 55. Monitoring wells placed below groundwater flow channels containing mine drainage. In the map view, monitoring wells would appear to be properly located. (Modified from R. R. Parizek, 1973).

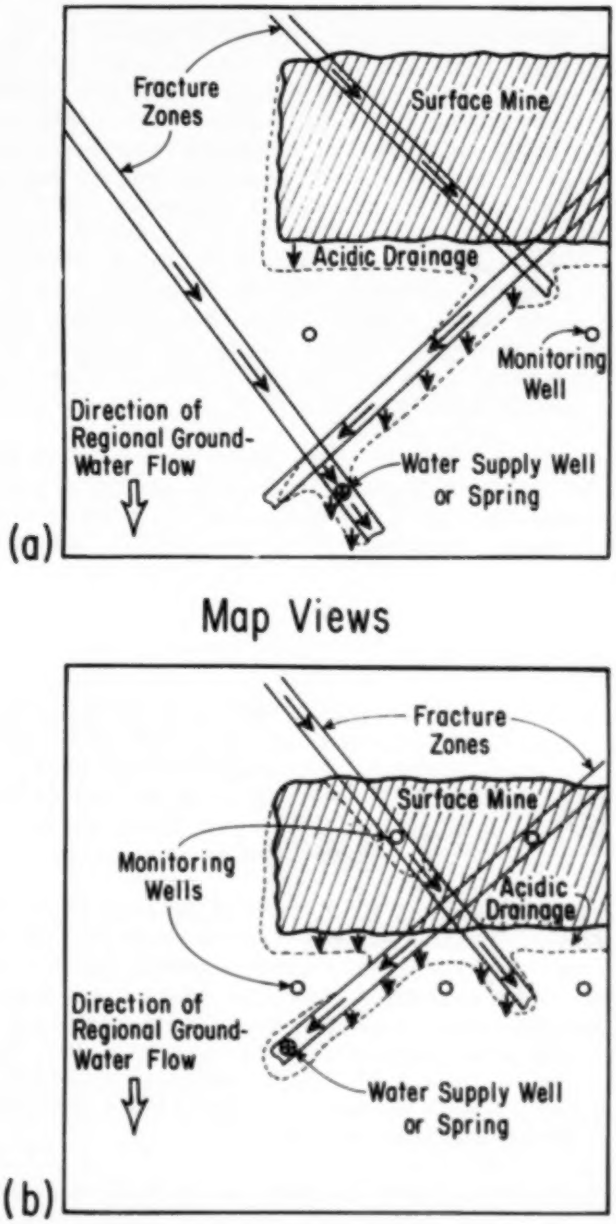

Fracture Zones
Surface Mine
Acidic Drainage
Monitoring Well
Direction of Regional Ground-Water Flow
Water Supply Well or Spring
(a)
Map Views
Fracture Zones
Surface Mine
Monitoring Wells
Acidic Drainage
Direction of Regional Ground-Water Flow
Water Supply Well or Spring
(b)

Figure 56. Fracture zones causing mine drainage to bypass monitoring wells. (Modified from R. R. Parizek, 1973).

mine discharge locations, etc. Soil water monitoring may be desirable at shallow depths in unsaturated soil and rock to determine early changes in soil water quality resulting from a particular land treatment practice.

Pressure-vacuum lysimeters (suction lysimeters) appear to be best adapted for obtaining soil water samples of reasonable size (Figure 57). The benefits and limitations of suction and pan lysimeters are given by Parizek and Lane (1970), along with suggestions for their installation. These devices can extract water under a state of tension, provided that there is (1) a hydraulic connection between capillary-sized openings in the unglazed porcelain tip of the device, and (2) soil backfilled around the point and soil or rock. The devices should be located within or below the soil water column to be sampled, because gravitation water will be derived from infiltration of surface water above the sample station in most cases. Lateral flow of soil water will occur under some field settings, which can result in the bypassing of soil water above or below a lysimeter. Nested or stacked lysimeters (3 to 4 per borehole) will reduce the chance of bypassing and allow for water quality change determination with depth or distance of travel.

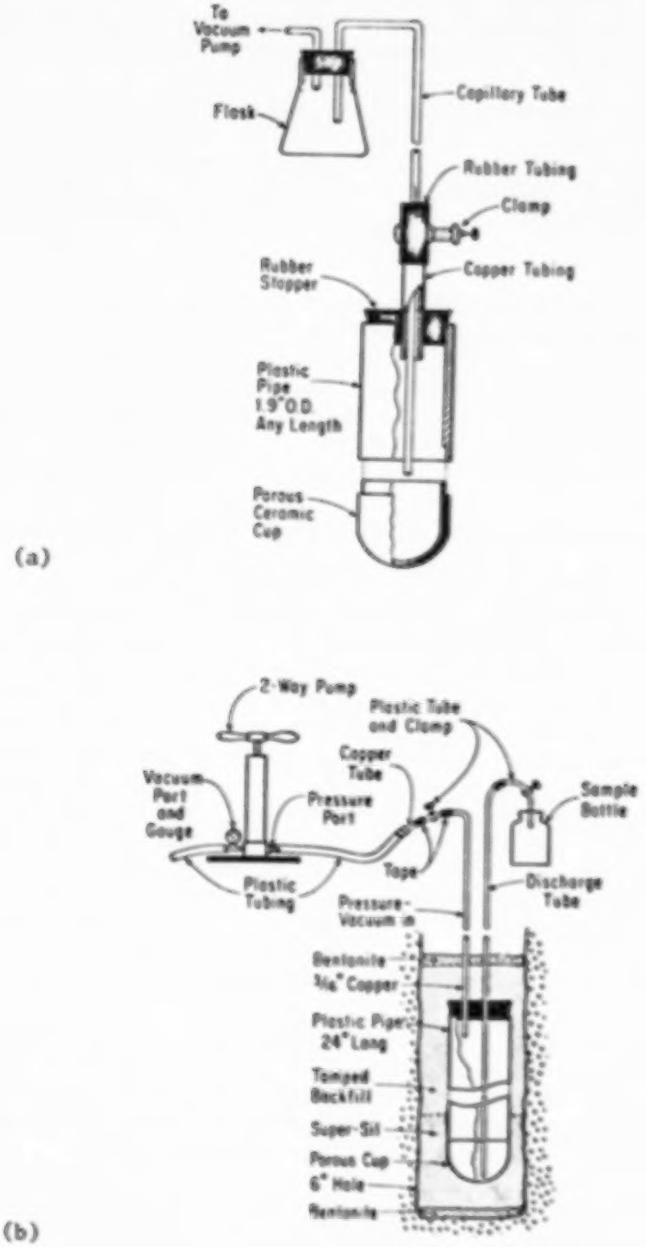
Pressure-vacuum lysimeters will provide water samples even when submerged within groundwater and no matter how coarse-textured the mine spoil. This will not be true for unsaturated spoil deposits, which require the presence of fine, capillary-sized pores immediately in contact with the porous porcelain tip of the sampler.

LONG-TERM CHANGES IN PRECIPITATION

Some adjustments in hydrologic budget values will be required when planning surface mines adjacent to existing and proposed power generating plants that rely on evaporative cooling to dissipate waste heat. Large-scale "energy parks" of the future that may contain mine mouth coal-fired plants together with nuclear-powered generating plants can place a significant daily consumptive draft on local and regional water resources.

The delays and costs of clearing four or five smaller power plants through environmental review procedures might prove greater than the time and money spent to win approval for a single 20,000-megawatt plant. C. Hosler (personal communication, 1976) indicates that the waste heat dissipation might approach the 40,000-megawatt range for such large-scale energy parks. This could require a 14,158-1/sec (500-cfs) made-up-demand for cooling water dissipated to the atmosphere. Such a 45.5-billion ℓ/day (10-billion gallon/day) consumptive demand can be made up using larger rivers and the Great Lakes of the more humid eastern United States.

Hosler points out that waste heat in this amount will produce convective patterns that will have important effects on downwind weather conditions. Precipitation increases of approximately 127 mm (5 in) would be possible 32 to 40 km (20 to 25 miles) downwind, especially during the summer months! This together with increased cloud cover, fog, etc. will suppress evapotranspiration, increase infiltration, groundwater recharge, and surface runoff.



To Vacuum Pump
Flask
Capillary Tube
Rubber Tubing
Clamp
Rubber Stopper
Copper Tubing
Plastic Pipe 1.9" O.D. Any Length
Porous Ceramic Cup
(a)
2-Way Pump
Plastic Tube and Clamp
Copper Tube
Vacuum Port and Gauge
Pressure Port
Sample Bottle
Tape
Plastic Tubing
Discharge Tube
Pressure-Vacuum in
Bentonite
1/4" Copper
Plastic Pipe 24" Long
Tamped Backfill
Super-Sil
Porous Cup
6" Hole
Bentonite
(b)

Figure 57. Pressure-vacuum lysimeters used to obtain water within the zone of aeration above the water table. (Source: Parizek and Lane, 1970).

A 102- to 152-mm (4- to 6-in) annual increase in precipitation would greatly increase the volume of mine drainage produced at active and abandoned coal mines during both the growing and nongrowing seasons.

Elevated plumes 1,524 to 2,134 m (5,000 to 7,000 ft) high on cold mornings could be visible to ground observers 161 km (100 miles) away. Lightning and hail frequencies should increase downwind, and precipitation should become more mineralized. These and related problems, Hosler indicates, could be minimized or eliminated by scattering more plants in the 500-megawatt capacity.

Salts and dissolved mineral matter from cooling water pose other problems because these will accumulate in the atmosphere and be returned by precipitation. Surface water impacted by acid mine drainage and used for evaporative cooling would add to this problem. Hosler estimated that fresh river water might deliver approximately 112 to 336 kb/hectare (100 to 300 lb/acre) of salt through precipitation fallout. Sea water used for cooling, by contrast, might return up to 1.121 kb/hectare (1,000 lb/acre) of salt near the plant.

Still other longer-term trends in precipitation require attention because of their impact on mine drainage water quality. Acid precipitation (acid rainfall) in Scandinavian countries (where this phenomenon is considered a critical environmental problem) and in the northeastern United States and southeastern Canada is ascribed to increased combustion of fossil fuels by man, which relates large quantities of sulfur oxides and nitrogen oxides to the atmosphere. Harr and Coffey (1975) point out that sulfur dioxide and hydrogen sulfide are oxidized and hydrolyzed in the atmosphere to sulfuric acid at varying rates, depending on environmental conditions. Various nitrogen oxides are likewise transformed into nitric acid. These acids may be neutralized by alkaline substances also present in the atmosphere, such as calcite or dolomite dust particles, or they will ultimately fall to the land and water surfaces with precipitation. Neutralization may occur here, provided that sources of alkalinity are available within soil water, groundwater, streams and lakes, soils or rock strata. If these upland watersheds, streams, and lakes lack a buffering capacity, they in turn will become acidic in time with various longer-term environmental difficulties.

Of special concern to mine planning is the possible development of acid and related pollution problems in strip mines that may be induced by acid rain but are attributed to mining. Pollution abatement measures may thus be required by the mining industry, when in fact, some costs should be shared by the segments of society that generate and use energy.

A related problem could develop from the combined effects of mining and the decreased pH of precipitation. For example, bacteria have been shown to be important in catalyzing acid reactions by accelerating the pyrite oxidation process. Iron-oxidizing bacteria (*Thiobacillus ferrooxidans*, *Ferrobacillus ferrooxidans*) and sulfide-oxidizing bacteria (*Thiobacillus thiooxidans*) have been found in great quantities in mine drainage. Singer and Stumm (1970) state that abiotic oxidation of ferrous iron to ferric iron proceeds very slowly where pH is less than 4.0; the presence of iron-oxidizing bacteria accelerates this reaction by a factor greater than 10^6. Some mine spoils are only mildly acid reactive and do not require special water treatment facilities during and following mining for waters to meet local standards. But a drop in soil and groundwater pH as a result of acid precipitation combined with pyrite oxidation could bring about a reduction in pH approaching optimum values for stimulating these bacteria. The rates of future acid reactions could thus be greatly accelerated. In other words, mine spoils producing water of favorable or tolerable quality may begin to produce acid reactions at an accelerating rate in the future, partly for external reasons.

If indeed such a mechanism is possible and current trends in precipitation pH continue, a new dimension of water quality problems may be thrust on both the mining industry and regulatory agencies.

Recent declines of trout and salmon stocks in streams and lakes of Sweden, Norway, and Finland have been attributed to inorganic acids derived from man's activities in northern Europe (Bolin, 1971; Jensen and Snekvik, 1972; Oden and Ahl, 1973).

Similarly, fallout of inorganic acids in rain and snow has been reported to have severely affected aquatic vegetation and fish populations in numerous southern Ontario lakes located on the igneous and metamorphic rocks that make up the Canadian shield (Overrein, 1972; Gorham and Gordon, 1963; and Beamish, 1974).

Harr and Coffey (1975) summarize the variety of environmental influences acid rain can have on the environmental setting in the long term. These changes have been slow in coming and have only recently been accelerated by man's activities. Impacts can be to limnology and aquatic biology, vegetation, soil leaching and weathering, forests and soils, biotic components of soils, and health.

Data on pH of rainfall in the eastern United States appears to be scant before 1962 (Gambell and Fisher, 1966; Likens and Borman,1974), and the case for increased acidity of precipitation is not as well documented as for Scandinavian countries (Bolin, 1971; Oden, S., 1968; Oden and Ahl, 1973; Lundholm, 1970; and Reiquam, 1970). However, Cogbell and Likens (1974), employing chemical data published by others, made predictions of pH values for the northeastern United States for the periods 1955-56 and 1965-66 (Figures 58 and 59).

The most striking feature their plots reveal is the size of the area in 1955-56 that had a pH of less than 5.6 (Figure 58). In fact, a large region in the northeast had average pH values below 4.52. These predictions (many values were not based on actual observations) suggest that acid precipitation was prevalent over most of the eastern United States by 1955-56. Their 1965-66 predictions (Figure 59) show a similar pattern, but with an increased land area receiving precipitation having a pH of less than 5.6, including extensive areas to the northwest and southwest that fall within coalfields of the Michigan Basin, Illinois Basin, and central Appalachian region. These and other authors conclude that the exponential increase in consumption of fossil fuels and mineral deposits since the advent of the industrial

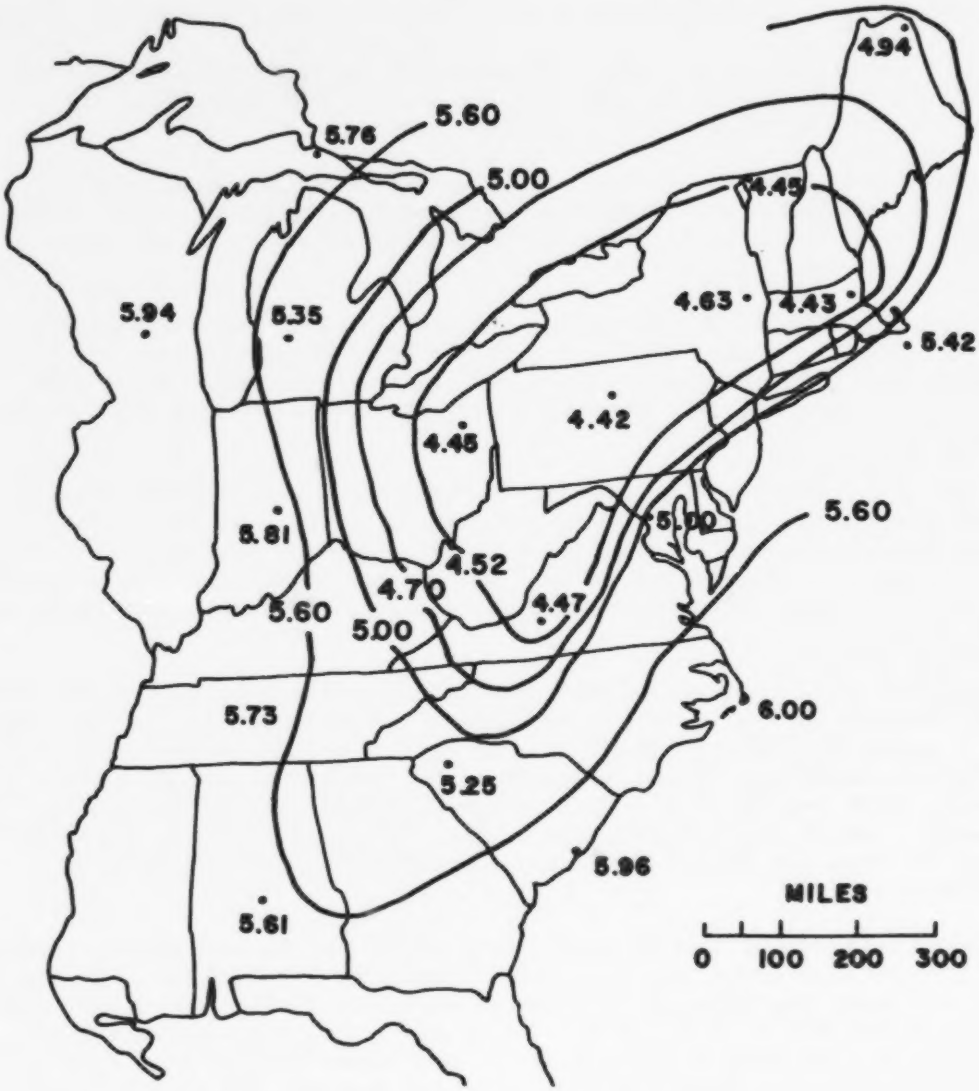

4.94
5.60
5.76
5.00
4.45
5.94
5.35
4.63
4.43
5.42
4.42
4.45
5.60
5.81
5.00
4.52
4.70
4.47
5.60
5.00
5.73
6.00
5.25
5.96
MILES
0
100
200
300
5.61

Figure 58. Predicted pH of precipitation over the eastern United States during the period 1955-56, based on chemical data of Junge (1958) and Junge and Werby (1958). (From Cogbell and Likens, 1974).

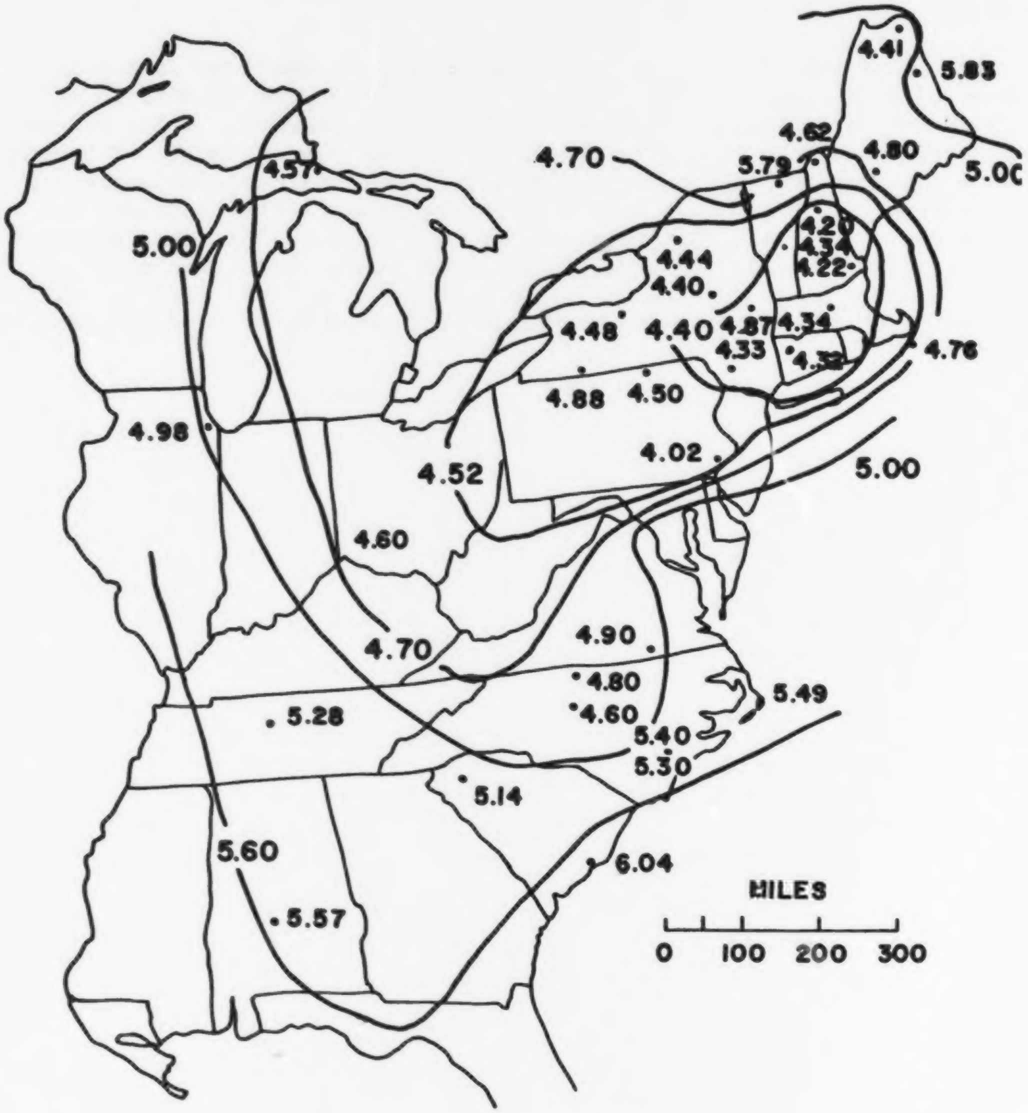

4.41
5.83
4.62
4.70
5.79
4.80
5.0
4.57
5.00
4.20
4.34
4.22
4.44
4.40
4.48
4.40
4.87
4.34
4.33
4.32
4.76
4.88
4.50
4.98
4.02
4.52
5.00
4.60
4.70
4.90
4.80
5.49
5.28
4.60
5.40
5.30
5.14
5.60
6.04
MILES
5.57
0
100
200
300

Figure 59. Predicted pH of precipitation over the eastern United States during the period 1965-66, based on chemical data of Lodge et al., (1958) and Gambell and Fisher (1966). (From Cogbell and Likens, 1974).

revolution has altered geochemical cycles and modified atmospheric chemistry in the heavily industrial North Temperate Zone. This trend is bound to continue.

Precipitation with low pH values may become an important factor in regions of North America other than in the Shield regions of Ontario and New York (areas influenced by surface mining, for example). Soils and surface streams and lakes that lack a natural buffer capacity might be expected to show a steady decline in pH as a result of decreased precipitation pH. Fortunately, vast regions of North America contain a buffer capacity in shallow soil, bed rock, surface water, and groundwater. The acid precipitation problem is likely to have its earliest impact where acid spoil is already causing mine drainage pollution problems. Here, it could accelerate the rate of acid production and counteract the benefits of mine restoration attempts.

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GLOSSARY

Acidic overburden - strata overlying a coal seam that, when contacted by water, has the potential for making it acidic.

Alkaline overburden - strata overlying a coal seam that, when contacted by water, has the potential for making it alkaline.

Aquifer - a stratum or zone below the surface of the earth capable of storing, transporting, or producing water, as from a well.

Attrition - an autogeneous process that maintains surfaces of solids clean and free of foreign substances, such as reaction products. It results from frictional action upon contact of two particles.

Autotrophic - needing only inorganic compounds for nutrition.

Basicity - the available alkalinity in a material that may be used in a neutralization process.

Biochemical oxidation - a process in which substances such as pyrite and ferrous sulfate are oxidized to a higher oxidation state by some mechanism in which the metabolic life process predominates.

Calcined - subjected to very high temperatures that change the composition of a material (such as calcined lime, which is prepared by the heating of limestone and the subsequent removal of carbon dioxide).

Cation exchange reaction - the replacement of undesirable cation or anion components in coal mine drainage by more acceptable soluble ions by solubility principles.

Coal mine drainage (CMD) - water transferred from a coal mine environment. Such waters usually have enhanced dissolved solids and poor quality.

Effluent - a liquid, solid, or gaseous product or waste leaving a treatment process or system.

Feed or raw water - water entering a treatment process or system. This term is usually applied to those waters entering the first stage of a treatment system.

Flocculant - a surfactant reagent that enhances the agglomeration of very fine particles to settleable flocs.

Heterotrophic - obtaining nourishment primarily from organic matter.

Influent - a material stream (liquid, solid, or gaseous) entering a treatment process.

Leaching - a solution process whereby the desired metal is recovered directly from the ore. Leaching can occur in situ or in specially prepared dumps.

Lineament - significant lines of landscapes that reveal the hidden architecture of the rock basement. Such areas typically have greater water permeability than the adjacent terrain.

Lixiviant - a solution enhancing the solubility of certain or all components of a material.

Mineralized waters - waters that contain soluble mineral substances acquired by the water when passing through strata of the earth.

Neutralization - a chemical reaction or process that decreases the hydrogen ion content of coal mine drainage.

Neutralization equivalent - the quantity of chemical needed to react completely and without excess in a neutralization reaction. The quantity is consistent with that defined stoichiometrically by a balanced chemical equation.

Phytogenetic - of plant origin.

Polluted water - waters containing substances that are inimical to normal utilization and that are not indigenous to most waters. The term used is not restricted to biological contamination.

Reactivity - the extent of response, usually chemical, between two or more materials.

Settleability - an arbitrary concept for the behavior of solids in a fluid which seeks to describe a variety of settling characteristics.

Slaking - a hydration process that converts calcined lime to hydrated lime.

Sludge - a thick, aqueous suspension of sparingly soluble materials that are usually (but not necessarily) composed of valueless waste substances.

Slurry - a dilute aqueous suspension of a sparingly insoluble material.

Toxic material - material in the overburden that contributes poisonous components to the environment.

Yellowboy process - a conventional method of treating coal mine drainage by the addition of hydrated lime, followed by oxidation of ferrous iron by air and the separation of insoluble impurities by sedimentation.

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